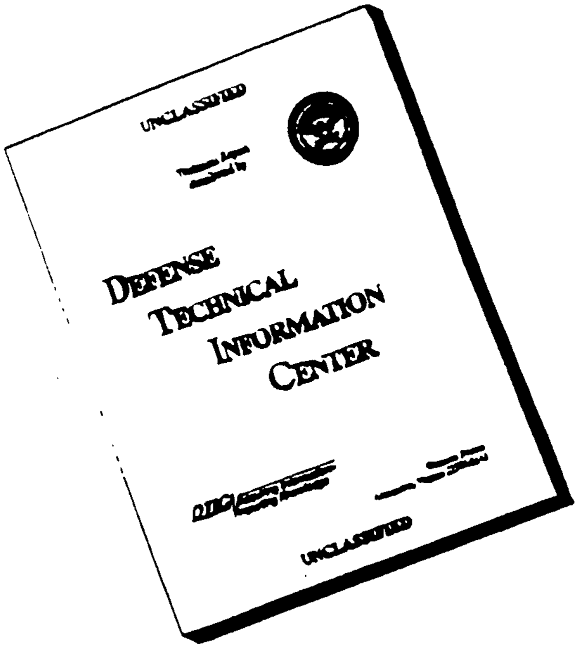
VOLUME III
SYSTEMS PHASE

CHAPTER 6A
ELECTRONIC WARFARE/RADAR HANDBOOK

JANUARY 1990

USAF TEST PILOT SCHOOL
EDWARDS AFB, CA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CONTENTS

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Rules of Thumb & Quick Estimates

1. Indicated Mach number x 10 = TAS in miles per minute.

   Example: .8 Mach x 10 = 8 miles/min TAS

   Accuracy ± 5% from 12,000' to 80,000' std day.

2. TAS in miles/min x 100 = TAS in ft/sec.

   Example: 8 miles/min TAS x 100 = 800 ft/sec

   Accuracy = 1.25%

3. Indicated Mach no x 1000 = TAS in fps

   Example: .8 Mach x 1000 = 800 ft/sec

   Accuracy ± 6% from 12,000' to 80,000' std day.

4. One degree (1°) covers 1000' at 10 miles

   This can be extended to 2000' @ 20 miles etc. or on to 6000' (1 mile) at 60 miles for each degree.

   Accuracy -5% (degrades with larger angles)

5. TACAN Ground Speed Checks

   Ground speed in knots = distance (nautical miles) traveled in 36 seconds X 100

   Quick Check: Ground speed in knots = distance traveled in nautical miles in 36 sec x 100.

   Example: 4.5 nmi in 36 sec x 100 = 450 KTS GS.

6. Turning Performance Estimates (level turns)*

   A. Rate of turn (ROT) = $\dfrac{\text{normal load factor (g)}}{\text{TAS in hundreds of knots}} \times 10$ deg/sec

   Example: [For flight conditions of 6 g's @ 600 KTAS]

   $\dfrac{6}{6} \times 10 = 10$ deg/sec rate of turn

   B. Radius of turn (r) = $\dfrac{(\text{TAS in hundreds of knots})^2}{\text{Normal load factor (g)}} \times 1000$ ft

   Example: [For flight conditions of 6 g's @ 600 KTAS]

   $\dfrac{6^2}{6} \times 1000 = \dfrac{36}{6} \times 1000 = 6000$ feet radius of turn

*These estimates are accurate within 10% at g levels of 2, 3, or 6, 7, and 8. At g levels of 4 and 5, the accuracy is within 17%.

CONVERSION FACTORS

To Convert	Into	Multiply By
degrees	mils	17.778
degrees	radians	0.01745
degrees	revolutions	0.002778
degrees/second	revolutions/minute	0.1661
feet	kilometers	0.0003048
feet	meters	0.3048
feet	miles (nautical)	0.0001645
feet	miles (statute)	0.0001894
feet/second	kilometers/hour	1.097
feet/second	knots	0.5922
feet/second	meters/second	0.3048
feet/second	miles/hour (statute)	0.6818
kilometers	feet	3281.0
kilometers	meters	1000.0
kilometers	miles (nautical)	0.5397
kilometers	miles (statute)	0.6214
kilometers/hour	feet/second	0.9113
kilometers/hour	knots	0.5397
kilometers/hour	meters/second	0.2778
kilometers/hour	miles/hour (statute)	0.6214
knots	kilometers/hour	1.8532
knots	miles/hour (nautical)	1.0
knots	miles/hour (statute)	1.151
knots	feet/second	1.689
knots	meters/second	0.515
meters	feet	3.281
meters	kilometers	0.001
meters	miles (nautical)	0.0005396
meters	miles (statute)	0.0006214
meters/second	feet/second	3.281
meters/second	kilometers/hour	3.6
meters/second	knots	1.942
meters/second	miles/hour (statute)	2.237
miles (nautical)	feet	6080.3
miles (nautical)	kilometers	1.853
miles (nautical)	meters	1853.0
miles (nautical)	miles (statute)	1.1516
miles (statute)	feet	5280.0
miles (statute)	kilometers	1.609
miles (statute)	meters	1609.0
miles (statute)	miles (nautical)	0.8684
miles/hour (nautical)	knots	1.0
miles/hour (statute)	feet/second	1.467
miles/hour (statute)	kilometers/hour	1.609
miles/hour (statute)	knots	0.8684
miles/hour (statute)	meters/second	0.4469
milliradians	radians	0.001
milliradians	mils	1.0186
mils	degrees	0.05625
mils	milliradians	0.9817
radians	degrees	57.3
revolutions	degrees	360.0
revolutions/minute	degrees/second	6.0

Mach. to Knots Conversions at Standard Atmosphere

Altitude in Feet	1	.95	.9	.85	.8	.75
	Approximate Knots at Mach No.					
0	662	629	596	562	529	496
1000	660	627	594	561	528	495
2000	657	624	591	558	526	493
3000	655	622	589	557	524	491
4000	653	620	587	555	522	490
5000	650	618	585	553	520	488
6000	648	616	583	551	518	486
7000	646	614	581	549	516	485
8000	643	611	579	547	515	483
9000	641	609	577	545	513	481
10000	639	607	575	543	511	479
12000	634	602	570	539	507	476
14000	629	598	566	535	503	472
16000	624	593	562	530	499	468
18000	619	588	557	526	495	464
20000	615	584	553	522	492	461
22000	610	580	549	518	488	458
24000	605	575	545	514	484	454
26000	600	570	540	510	480	450
28000	595	565	536	506	476	446
30000	590	561	531	502	472	443
32000	585	556	526	497	468	439
34000	580	551	522	493	464	435
36000 and above	575	546	517	489	460	431

Mach to Knots Conversions at Standard Atmosphere

.7	.65	.6	.55	.5	.45	.4	Altitude in Feet
Approximate Knots at Mach No.							
463	430	397	364	331	298	265	0
462	429	396	363	330	297	264	1000
460	427	394	361	329	296	263	2000
458	426	393	360	328	295	262	3000
457	424	392	359	327	294	261	4000
455	423	390	358	325	293	260	5000
454	421	389	356	324	292	259	6000
452	420	387	355	323	291	258	7000
450	418	386	354	322	289	257	8000
449	417	385	353	321	288	256	9000
447	415	383	351	320	287	255	10000
444	412	380	349	317	285	254	12000
440	409	377	346	315	283	252	14000
437	406	374	343	312	281	250	16000
433	403	371	340	310	279	248	18000
430	400	369	338	308	277	246	20000
427	397	366	336	305	275	244	22000
424	393	363	333	303	272	242	24000
420	390	360	330	300	270	240	26000
417	387	357	327	298	268	238	28000
413	384	354	325	295	266	236	30000
409	380	351	322	293	263	234	32000
406	377	348	319	290	261	232	34000
402	374	345	316	288	259	230	36000 and above

Standard Atmosphere

Alt Ft	Temp. °F	Temp. °C	Press. in. Hg.
0	59.0	15.0	29.92
1000	55.4	13.0	28.86
2000	51.9	11.0	27.82
3000	48.3	9.1	26.82
4000	44.7	7.1	25.84
5000	41.2	5.1	24.90
6000	37.6	3.1	23.98
7000	34.0	1.1	23.09
8000	30.5	-0.8	22.22
9000	26.9	-2.8	21.38
10000	23.3	-4.8	20.58
11000	19.8	-6.8	19.79
12000	16.2	-8.8	19.03
13000	12.6	-10.8	18.29
14000	9.1	-12.7	17.58
15000	5.5	-14.7	16.89
16000	1.9	-16.7	16.22
17000	-1.6	-18.7	[illegible]
18000	-5.2	-20.7	14.94
19000	-8.8	-22.6	14.34
20000	-12.3	-24.6	[illegible]
21000	-15.9	-26.6	13.18
22000	-19.5	-28.6	12.64
23000	-23.0	-30.6	12.11
24000	-26.6	-32.5	11.60
25000	-30.2	-34.5	11.10
26000	-33.7	-36.5	10.63
27000	-37.3	-38.5	[illegible]
28000	-40.9	-40.5	9.72
29000	-44.4	-42.5	9.29
30000	-48.0	-44.4	8.88
31000	-51.6	-46.4	8.45
32000	-55.1	-48.4	[illegible]
33000	-58.7	-50.4	[illegible]
34000	-62.2	-52.4	7.35
35000	-65.8	-54.3	[illegible]
36089	-69.7	-56.5	6.683
37000	-69.7	-56.5	[illegible]
38000	-69.7	-56.5	6.09
39000	-69.7	-56.5	[illegible]
40000	-69.7	-56.5	5.558
41000	-69.7	-56.5	5.278
42000	-69.7	-56.5	5.03
43000	-69.7	-56.5	4.794
44000	-69.7	-56.5	4.564
45000	-69.7	-56.5	4.355
46000	-69.7	-56.5	4.151
47000	-69.7	-56.5	3.956
48000	-69.7	-56.5	3.770
49000	-69.7	-56.5	3.593
50000	-69.7	-56.5	3.425

Temperature

°C	°F
-80	-112.0
70	-94.0
-60	-76.0
-50	-58.0
-40	-40.0
-30	-22.0
-25	13.0
-20	-4.0
-15	5.0
-10	14.0
-5	23.0
0	32.0
5	41.0
10	50.0
15	59.0
20	68.0
25	77.0
30	86.0
35	95.0
40	104.0
45	113.0
50	122.0
55	131.0
60	140.0
65	149.0
70	158.0
75	167.0
80	176.0
85	185.0
90	194.0
95	203.0
100	212.0
105	221.0
110	230.0
115	239.0
120	248.0
125	257.0
130	266.0
135	275.0
140	284.0
145	293.0
150	302.0
155	311.0
160	320.0
165	329.0
170	338.0
175	347.0

$$F^O=\frac{9C^O}{5}+32$$

$$C^O=\frac{5}{9}(F^O-32)$$

$$\text{Pivotal Altitude} = \frac{TAS^2(\text{smph})}{15}$$

Angle of 1° = 1 mile in 56 miles

Approximate Distance to Sea Level Horizon

Statute Miles	$\sqrt{1.76\text{xfeet above SL}}$
Nautical Miles	$\sqrt{1.33\text{xfeet above SL}}$

1 US Gallon of	gasoline	6. Pounds
	kerosene	6.75 Pounds
	oil	7.5 Pounds
	alcohol	6.6 Pounds
	water	8.33 Pounds

1 US Gallon	.83268 Imperial Gallons 231 cubic inches .134 cubic feet 3.785 liters
1 cubic foot	7.5 U.S. Gallons
Absolute Zero	-273.16° C = -459.688° F
Speed of Light	186.282 397 sm/second 299.784.25 Km/second

Gravity = 32.17405 ft/sec/sec
9.80665 meters/sec/sec

1 Horsepower = .7457 kilowatt
550 foot pounds/second

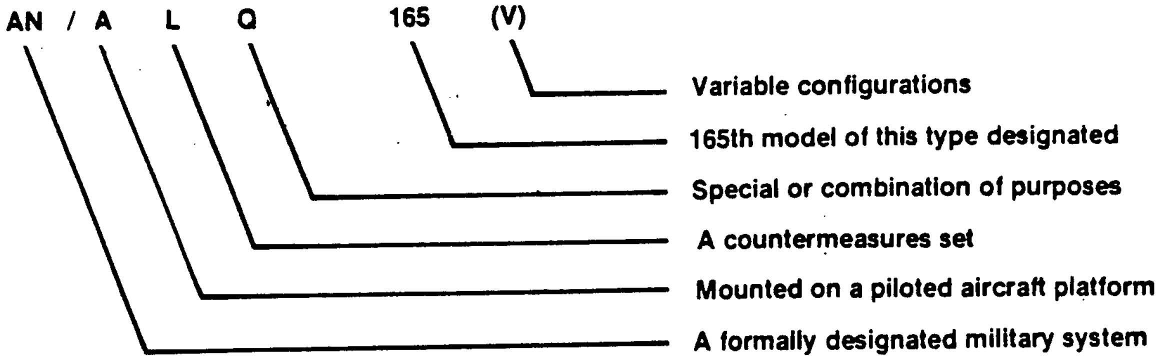
Circle Circumference	$\pi D = 2\pi R$
Circle Area	πR^2
Sphere Surface	πD^2
Sphere Volume	$\frac{\pi D^3}{6}$

Cylinder Volume $\pi R^2 \times \text{height}$

— NOTES —

Deciphering US Electronic Equipment Designations

Example of Assignment



Equipment Indicators

Platform Installation

A	Piloted aircraft
B	Underwater mobile, submarine
D	Pilotless carrier
F	Fixed ground
G	General ground use
K	Amphibious
M	Mobile (ground)
P	Portable
S	Water
U	General utility
V	Vehicular (ground)
W	Water surface and underwater combination
Z	Piloted-pilotless airborne vehicle combination

Equipment Type

A	Invisible light, heat radiation
C	Carrier
D	Radiac
G	Telegraph or teletype
I	Interphone and public address
J	Electromechanical or inertial wire covered
K	Telemetering
L	Countermeasures
M	Meteorological
N	Sound in air
P	Radar
Q	Sonar and underwater sound
R	Radio
S	Special or combinations of types
T	Telephone (wire)
V	Visual and visible light
W	Armament
X	Facsimile or television
Y	Data processing

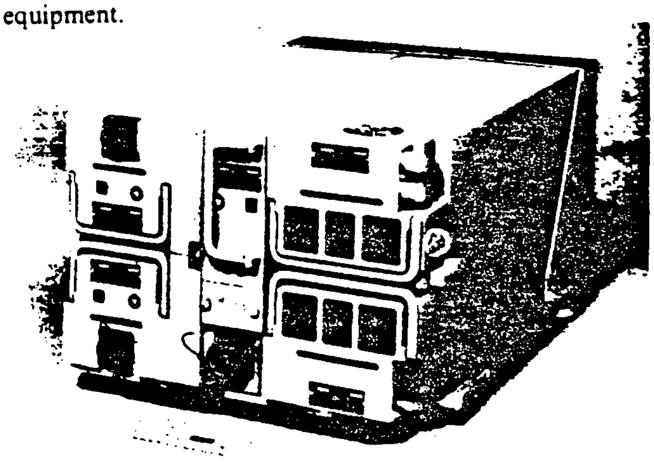
Equipment Function or Purpose

B	Bombing
C	Communications
D	Direction finder, reconnaissance and/or surveillance
E	Ejection and/or release
G	Fire control or search-light directing
H	Recording and/or reproducing
K	Computing
M	Maintenance and/or test assemblies
N	Navigational aids
Q	Special or combination of purposes
R	Receiving, passive detecting
S	Detecting and/or range and bearing, search
T	Transmitting
W	Automatic flight or remote control
X	Identification and recognition

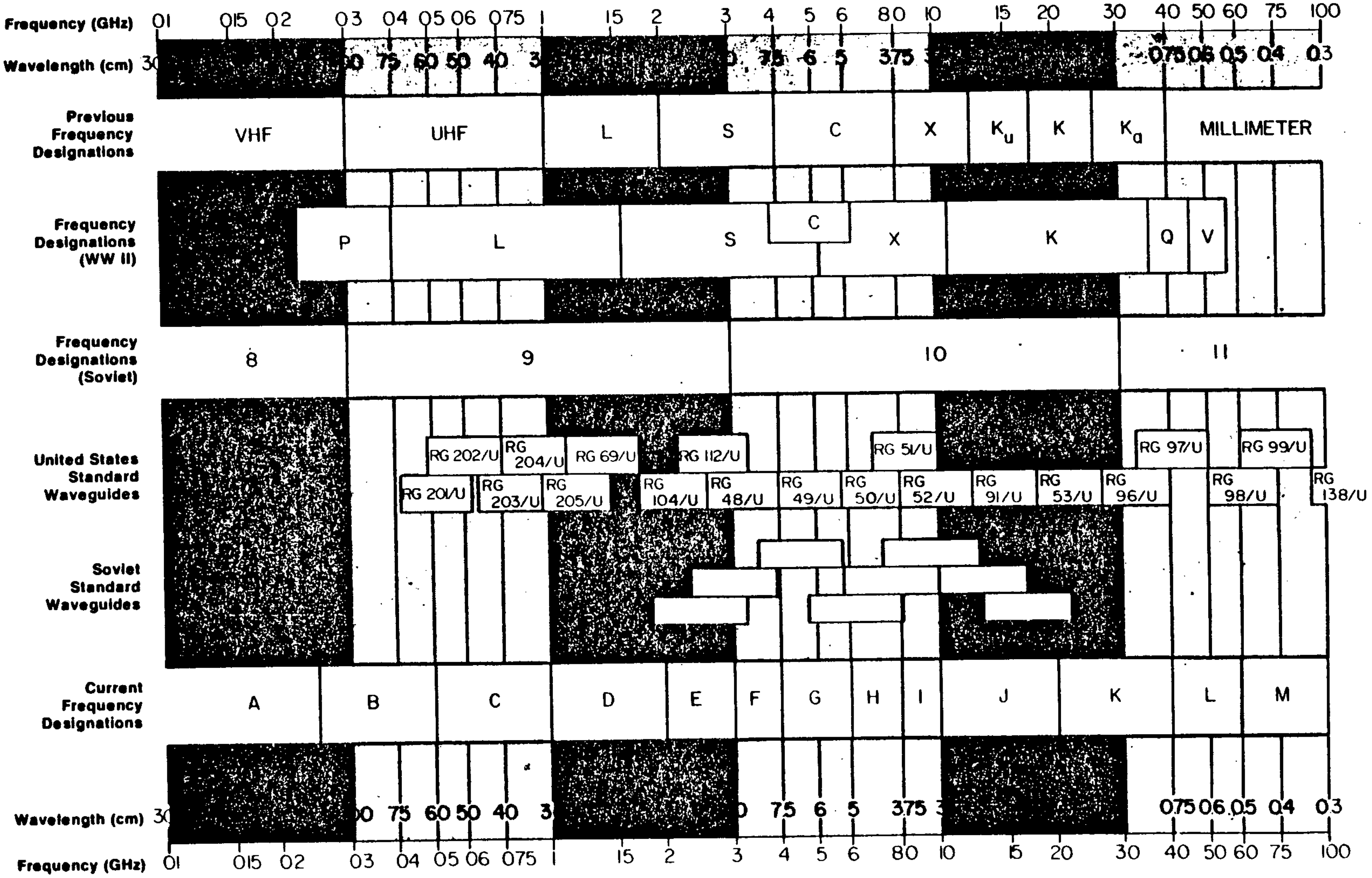
Designation Modifiers

Letters following the AN designation numbers provide added information about the equipment. Letters A, B, C, etc., indicate the latest modification. AN/ALR-67B would indicate the second modification to the system. The letter (V) indicates variable configurations are available. The letter (X) indicates developmental status. A double parenthesis ( ) indicates a generic system that has not yet received a formal designation, i.e., AN/ALQ-( ), or AN/ALQ-165( ). The double parenthesis is verbally referred to as "bowlegs."

All US military electronic equipment are assigned an identifying alphanumeric designation that can be used to determine the platform the equipment was designed to be operated on, the type of equipment, and the function of the equipment. This system is commonly called the AN designation system, although its formal name is the Joint Electronics Type Designation System (JETDS). The letters AN preceding the equipment indicators formerly meant Army/Navy, but are now considered to be an exclusive letter set that can only be used to indicate formally designated DOD equipment.



Frequency Designation Chart



Courtesy Sanders Associates

ECM Frequency Bands & Channel Codes

Band	Frequency in MHz	Channel Width MHz	Former Bands MHz	
A	0–250	25	I	100–150
B	250–500	25	G	150–225
C	500–1000	50	P	225–390
D	1000–2000	100	L	390–1550
E	2000–3000	100	S	1550–5200
F	3000–4000	100	C	3900–6200
G	4000–6000	200	X	6200–10,900
H	6000–8000	200	K	10,900–36,000
I	8000–10,000	200	Q	36,000–46,000
J	10,000–20,000	1000	V	46,000–56,000
K	20,000–40,000	2000		
L	40,000–60,000	2000		
M	60,000–100,000	4000		

Frequency List

Band and Channel	Frequency in MHz	Band and Channel	Frequency in MHz
A-1	0–25	B-1	250–275
A-2	25–50	B-2	275–300
A-3	50–75	B-3	300–325
A-4	75–100	B-4	325–350
A-5	100–125	B-5	350–375
A-6	125–150	B-6	375–400
A-7	150–175	B-7	400–425
A-8	175–200	B-8	425–450
A-9	200–225	B-9	450–475
A-10	225–250	B-10	475–500

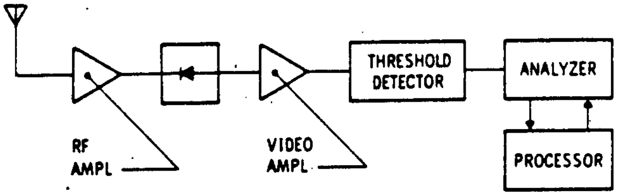
Frequency List

Band and Channel	Frequency in MHz	Band and Channel	Frequency in MHz
C-1	500–550	D-1	1000–1100
C-2	550–600	D-2	1100–1200
C-3	600–650	D-3	1200–1300
C-4	650–700	D-4	1300–1400
C-5	700–750	D-5	1400–1500
C-6	750–800	D-6	1500–1600
C-7	800–850	D-7	1600–1700
C-8	850–900	D-8	1700–1800
C-9	900–950	D-9	1800–1900
C-10	950–1000	D-10	1900–2000
E-1	2000–2100	F-1	3000–3100
E-2	2100–2200	F-2	3100–3200
E-3	2200–2300	F-3	3200–3300
E-4	2300–2400	F-4	3300–3400
E-5	2400–2500	F-5	3400–3500
E-6	2500–2600	F-6	3500–3600
E-7	2600–2700	F-7	3600–3700
E-8	2700–2800	F-8	3700–3800
E-9	2800–2900	F-9	3800–3900
E-10	2900–3000	F-10	3900–4000
G-1	4000–4200	H-1	6000–6200
G-2	4200–4400	H-2	6200–6400
G-3	4400–4600	H-3	6400–6600
G-4	4600–4800	H-4	6600–6800
G-5	4800–5000	H-5	6800–7000
G-6	5000–5200	H-6	7000–7200
G-7	5200–5400	H-7	7200–7400
G-8	5400–5600	H-8	7400–7600
G-9	5600–5800	H-9	7600–7800
G-10	5800–6000	H-10	7800–8000
I-1	8000–8200	J-1	10,000–11,000
I-2	8200–8400	J-2	11,000–12,000
I-3	8400–8600	J-3	12,000–13,000
I-4	8600–8800	J-4	13,000–14,000
I-5	8800–9000	J-5	14,000–15,000
I-6	9000–9200	J-6	15,000–16,000
I-7	9200–9400	J-7	16,000–17,000
I-8	9400–9600	J-8	17,000–18,000
I-9	9600–9800	J-9	18,000–19,000
I-10	9800–10,000	J-10	19,000–20,000

Frequency List

Band and Channel	Frequency in MHz	Band and Channel	Frequency in MHz
K-1	20,000–22,000	L-1	40,000–42,000
K-2	22,000–24,000	L-2	42,000–44,000
K-3	24,000–26,000	L-3	44,000–46,000
K-4	26,000–28,000	L-4	46,000–48,000
K-5	28,000–30,000	L-5	48,000–50,000
K-6	30,000–32,000	L-6	50,000–52,000
K-7	32,000–34,000	L-7	52,000–54,000
K-8	34,000–36,000	L-8	54,000–56,000
K-9	36,000–38,000	L-9	56,000–58,000
K-10	38,000–40,000	L-10	58,000–60,000
M-1	60,000–64,000		
M-2	64,000–68,000		
M-3	68,000–72,000		
M-4	72,000–76,000		
M-5	76,000–80,000		
M-6	80,000–84,000		
M-7	84,000–88,000		
M-8	88,000–92,000		
M-9	92,000–96,000		
M-10	96,000–100,000		

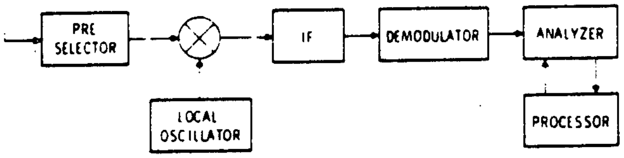
Receiver Comparisons



PRO	CON
●CHEAP ●VERY, VERY SMALL ●PROVEN TECHNOLOGY	● NO FREQ MEASUREMENT CAPABILITY ● ANALYZER HAS ONLY TOA & PW TO DETERMINE SIGNAL CHARACTERISTIC ● POOR SENSITIVITY ● VERY SUSCEPTIBLE TO ECCM ● DEGRADES QUICKLY IN DENSE SIGNAL ENVIRONMENT ● CANNOT HANDLE PRI AGILE RADARS

The hardware candidates to consider are: crystal video, superheterodyne, IFM, micro-scan systems, channelized receivers, Bragg cell systems and Surface Acoustic Wave dispersive delay lines. Only the common systems will be presented, and hybrid types will be avoided to keep the comparisons simple.

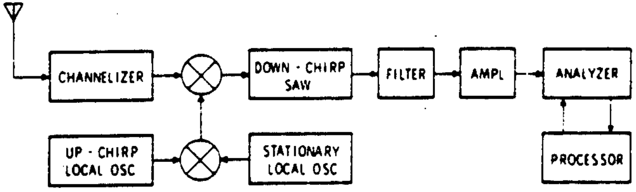
Crystal video receivers will be around forever. Its technology has been proven, it is very low cost and it does very well in limited applications. A crystal video system cannot make good fine frequency measurement, the analyzer has to handle a wide open system and cannot readily handle complex signals. Basically, it is incapable of handling frequency agile systems.



PRO	CON
●HIGH SELECTIVITY ●PROVEN DESIGN ●GOOD ECCM	●MINIMUM PULSE WIDTH >0.1 μS ●CANNOT SEE FREQUENCY AGILE SIGNALS ●SLOW SEARCH SPEED (RELATIVELY) ●TAKES TWO RECEIVERS FOR MONOPULSE DF

Superheterodyne

Looking at the superheterodyne system, the other most common system in the U.S. inventory, it is very good in some cases; and it is not susceptible to jamming. On the other hand, it takes a relatively long time to scan a frequency range. Minimum pulsewidths are determined by the bandwidths and a narrow bandwidth cannot be searched fast, so the tendency is to build wider RF front ends and search faster. Again, the frequency resolution becomes a problem. And in addition, to perform direction finding requires multiple receivers.



PRO	CON
● HIGH FREQUENCY ACCURACY < 1.0 MHZ ● SIMULTANEOUS SIGNAL RESOLUTION < 1.0 MHZ ● ACQUISITION BANDWIDTH ≈ 100 MHZ ● CAN HANDLE FREQUENCY AGILE	● REQUIRES CHANNELIZER ● MINIMUM PULSE WIDTH >0.1 μS ● CRITICAL SWEEP / SAW ALIGNMENT ● REQUIRES TWO RECEIVERS FOR MONOPULSE DF ● REQUIRES VERY WIDE IF BANDWIDTH

Microscan

A microscan technique will do away with some of the problems with the superheterodyne, because it is just a fast scan superhet. In this example, an up chirp local oscillator and a down chirp Surface Acoustic Wave dispersive delay line is used, which would allow a system to scan the frequency range within 1 radar pulse, thus giving a very high probability of detection. The system has many good qualities. It has a high probability detection, can handle wide band signals, has wide acquisition bandwidth and can handle frequency agile signals. But on the other hand, it requires a channelizer and the minimum pulsewidth cannot go much below 0.1 microsecond. A very critical alignment problem exists between the sweep and the dispersion delay line. And again, it requires multiple receivers for DF and a very wide IF bandwidth. The significance of the wide IF bandwidth is the overlap of signals and the inability of an operator to separate signals once the spectrum has been overlapped on the IF.

Channelized

A channelized receiver is an attempt to take a crystal video or a superhet and cover the RF spectrum in pieces. Take pieces of the spectrum, narrow them down and handle them one at a time. It gives several advantages: high selectivity, high probability of detection, and it is not susceptible to jamming. On the other hand, it is limited in frequency accu-

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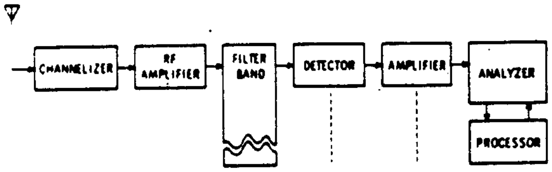
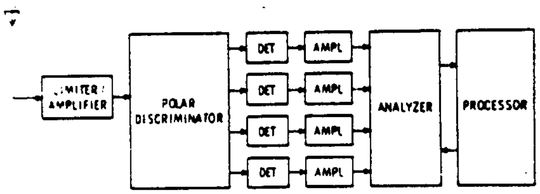
Excerpted from an article by R.C. Brown, GTE-Sylvania, in the 1977 edition of *The International Countermeasures Handbook*.

RECEIVER COMPARISONS



PRO	CON
● HIGH SELECTIVITY ● HIGH PROPABILITY OF DETECTION ● GOOD ECCM	● LIMITED FREQUENCY ACCURACY ● LIMITED RESOULTION ● MINIMUM PULSE WIDTH >0.1 µS ● REQUIRES CHANNELIZER ● CANNOT DO MONOPULSE DF

racy, because the system receives a channel at a time. The channelized receiver has limited resolution, because it can only handle pulsewidths inversely proportional to the bandwidth. It requires a channelizer and in general, cannot do monopulse DF, in a size and cost effective manner.



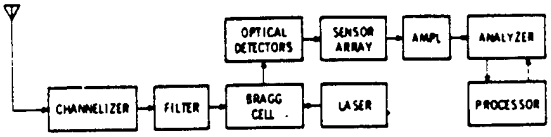
PRO	CON
● HIGH PROBABILITY OF DETECTION ● CAN HANDLE FREQUENCY AGILE SIGNALS ● PROVEN DESIGN ● FAIR FREQUENCY ACCURACY	● POOR SENSITIVITY ● POOR ECCM ● HIGH DATA RATE ● CANNOT HANDLE MULTIPLE SIMULTANEOUS SIGNALS ● CANNOT PERFORM MONOPULSE DF

IFM

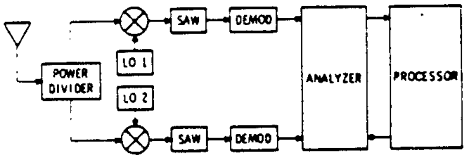
The instantaneous frequency measurement receiver (IFM) is nothing but a polar discriminator, but can give a high probability of detection and very good frequency measurement accuracy. It is a proven design and it can handle frequency agile signals. Conversely, the sensitivity isn't very good: it can be jammed, it doesn't handle a very high data rate well, unless the designer starts combining it with filters on the front end or tunable reject filters. It cannot handle simultaneous signals, it cannot handle CW signals, and it will always be an aid to the conventional systems for fast acquisition, but rarely can ever do the job all by itself.

Bragg Cell Operation

A Bragg cell is an optical crystal with special properties. Illuminating a Bragg cell with a laser beam and applying RF to the acoustic transducer in the Bragg cell, the acoustic wave will be propagated down the Bragg cell and the laser beam defracted by an amount in proportion to the stress (frequency) on the cell. Therefore, as different frequencies are propagated down the Bragg cell, the laser beam will defract a different amount. In a receiver, an array of photo detectors is used as the target, with each photo detector representing a channel of the receiver. This is basically a channelized receiver, but in this case a Bragg cell is used to separate the elements, instead of a number of filters. It is much smaller, cheaper, it has a high sensitivity, high probability of detection, and high selectivity. There are still problems with it and more development in the area of Bragg cells is needed. It is tough to handle frequency agile signals with a Bragg cell system because of the read out—it takes time to read out all the photo detectors. This system cannot measure pulse-width, because the pulsewidth information is lost when the photo detectors integrate a number of pulses. One has to do special things to the receiver to do monopulse DF and it is relatively slow in frequency search, primarily because the readout time of the photo-detectors.



PRO	CON
● HIGH PROBABILITY OF DETECTION ● HIGH SENSITIVITY ● MIN PULSE WIDTH <0.1 µS ● HIGH SELECTIVITY	● REQUIRES CHANNELIZER ● SLOW SEARCH BECAUSE OF SENSOR ARRAY READOUT ● CANNOT HANDLE FREQUENCY AGILE SIGNALS ● CANNOT MEASURE PULSE WIDTH ● TAKES TWO RECEIVERS TO DO MONOPULSE DF ● UNPROVEN HARDWARE



PRO	CON
● HIGH PROBABILITY OF DETECTION ● HIGH SENSITIVITY ● MINIMUM PULSE WIDTH < 0.1 µS ● CAN HANDLE FREQUENCY AGILE SIGNALS ● HIGH DYNAMIC RANGE ● HIGH REPETITION OF ELEMENTS FOR PRODUCTION ● MONOPULSE DF WITH ONE RECEIVER ● GOOD ECCM	● MODERATE TIME RESOLUTION OF PULSES ● UNPROVEN HARDWARE

Surface Acoustic Wave Receiver

The Surface Acoustic Wave system has been set up using two channels, two dispersive delay lines, to get a broader bandwidth than could be obtained with one. In addition, using two channels eliminates the need for preselection, because image response is handled in the processing. Also, a two channel system is adaptable to direction finding. This system has a high probability of detection, good sensitivity, minimum pulsewidth, can handle frequency agile signals, and has a good high dynamic range. It can handle multiple signals, can do monopulse DF with a single receiver and it is very hard to jam. On the other hand, there are some disadvantages: it takes a moderate time to resolve pulses that are close together, and basically the hardware is not fully mature.

System Antenna Selection Criteria

To help select the proper antenna for a particular EW system, it's often only necessary to answer three fundamental questions:

Is an omnidirectional antenna (one covering 360 degrees in azimuth), or a directional antenna, with a narrower antenna beam, required?

Omnidirectional antennas are used where coverage in all directions is required for warning and/or intercept functions; and for sidelobe suppression and qualification of signals in conjunction with direction finding systems. "Omnis" are also used for self-protection fuze jamming.

Directional antennas are fundamental with direction finding systems, high gain intercept systems, directional jamming systems and radars.

Does the system require a linearly or circularly polarized antenna?

Linear polarization is used when the other antenna is of known linear polarization, and it is desired to optimize the gain of the system; or if polarization analysis is to be performed.

Circular polarization is desirable when the polarization of the other antenna is unknown or variable, or if polarization diversity for any other reason is required.

Should the antenna cover a broad frequency band of an octave or more, or will a narrow band antenna meet the requirements of the system?

Once these alternatives have been considered, the choice of antennas can be narrowed down to only a few, in Table I. The chart in Table II, listing the general characteristics of the various antenna types, narrows the choice even further.

Courtesy: Klaes Elfving, GTE-Sylvania

Table I
System Requirements

Pattern	Polarization	Bandwidth	Antenna Type
Omnidirectional Antenna	Linearly Polarized	Narrow Band	Dipole Loop
		Broad Band	Biconical Swastika
	Circularly Polarized	Narrow Band	Normal Mode Helix
		Broad Band	Biconical w/Polarizer Lindenblad 4-Arm Conical Spiral
Directional Antenna	Linearly Polarized	Narrow Band	Yagi Dipole Array
		Broad Band	Log Periodic Horn
	Circulatory Polarized	Narrow Band	Axial Mode Helix Horns w/Polarizers
		Broad Band	Cavity Spirals Conical Spirals

Table II. Antenna Characteristics

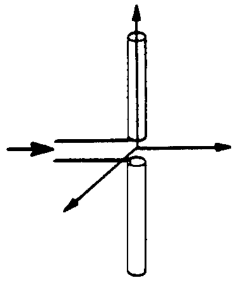
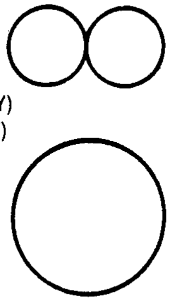
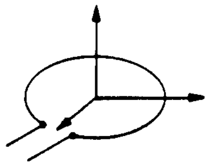
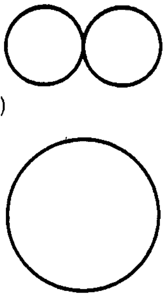
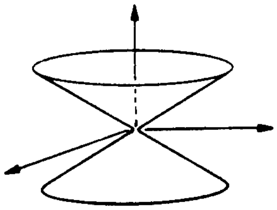
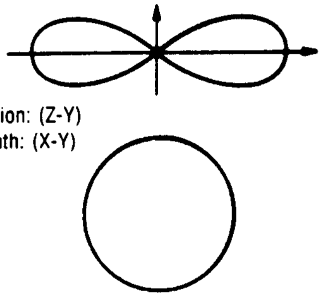
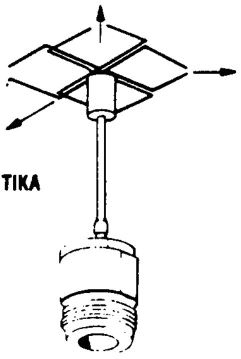
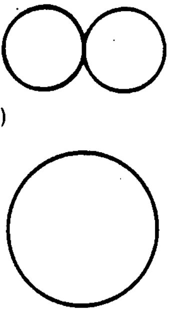
Antenna Type	Radiation Pattern	Specifications
DIPOLE 	 Elevation: (Z-Y) Azimuth: (X-Y)	**Polarization** Vertical **Typical Half-Power Beamwidth** 80° x 360° **Typical Gain** 2 dB **Bandwidth** 10% **Frequency Limit** **Lower:** None **Upper:** 8 GHz
LOOP 	 Elevation: (Z-Y) Azimuth: (X-Y)	**Polarization** Horizontal **Typical Half-Power Beamwidth** 80° x 360° **Typical Gain** −2 dB **Bandwidth** 10% **Frequency Limit** **Lower:** 50 MHz **Upper:** 1 GHz
BICONICAL 	 Elevation: (Z-Y) Azimuth: (X-Y)	**Polarization** Vertical **Typical Half-Power Beamwidth** 20°–100° x 360° **Typical Gain** 0 to 4 dB **Bandwidth** 4:1 **Frequency Limit** **Lower:** 500 MHz **Upper:** 40 GHz
 **SWASTIKA**	 Elevation: (Z-Y) Azimuth: (X-Y)	**Polarization** Horizontal **Typical Half-Power Beamwidth** 80° x 360° **Typical Gain** −1 dB **Bandwidth** 2:1 **Frequency Limit** **Lower:** 100 MHz **Upper:** 12 GHz

Table II. Antenna Characteristics

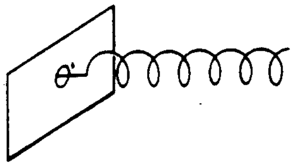
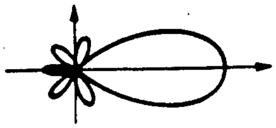
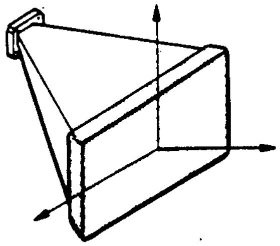
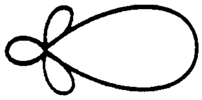
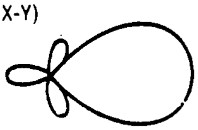
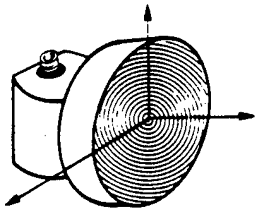
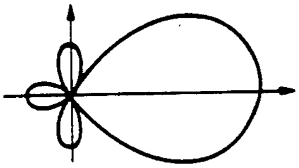
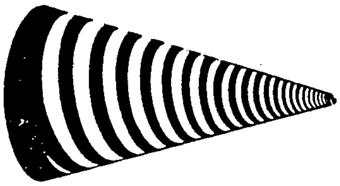
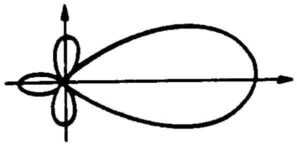
Antenna Type	Radiation Pattern	Specifications
AXIAL MODE HELIX 	Elevation & Azimuth 	**Polarization** Circular **Typical Half-Power Beamwidth** 50° x 50° **Typical Gain** 10 dB **Bandwidth** 1.7:1 **Frequency Limit** **Lower:** 100 MHz **Upper:** 3 GHz
HORNS WITH POLARIZER 	 Elevation: (Z-Y) Azimuth: (X-Y) 	**Polarization** Circular **Typical Half-Power Beamwidth** 40° x 40° **Typical Gain** 5 to 10 dB **Bandwidth** 3:1 **Frequency Limit** **Lower:** 2 GHz **Upper:** 18 GHz
CAVITY BACKED SPIRAL 	Elevation & Azimuth 	**Polarization** Circular **Typical Half-Power Beamwidth** 60° x 90° **Typical Gain** 2 to 4 dB **Bandwidth** 9:1 **Frequency Limit** **Lower:** 500 MHz **Upper:** 18 GHz
CONICAL SPIRAL 	Elevation & Azimuth 	**Polarization** Circular **Typical Half-Power Beamwidth** 60° x 60° **Typical Gain** 5 to 8 dB **Bandwidth** 4:1 **Frequency Limit** **Lower:** 50 MHz **Upper:** 18 GHz

Table II. Antenna Characteristics

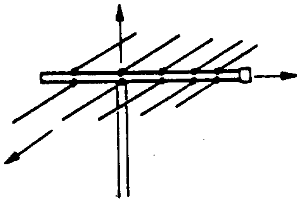
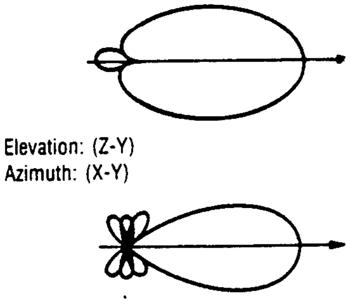
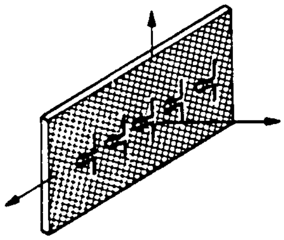
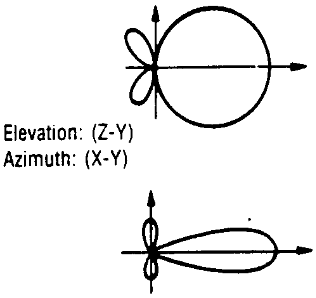
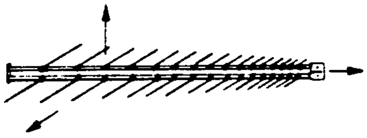
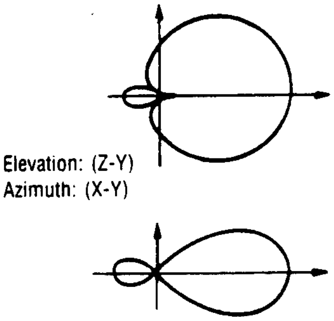
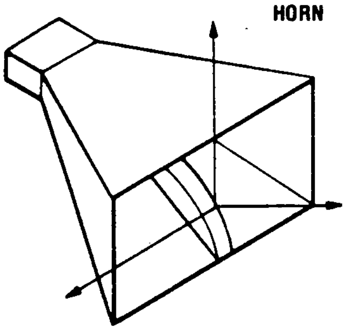
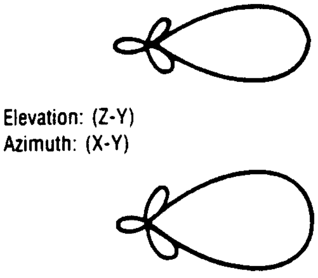
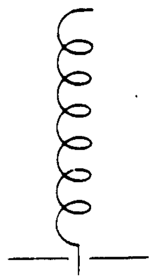
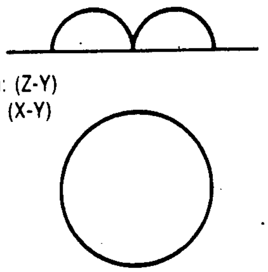
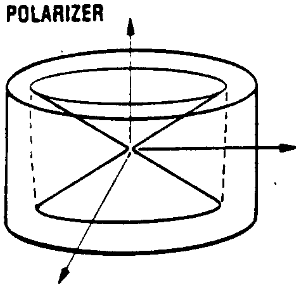
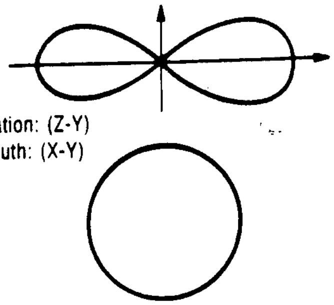
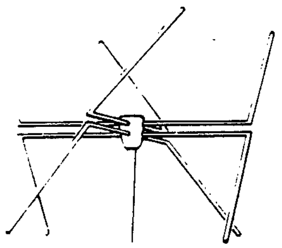
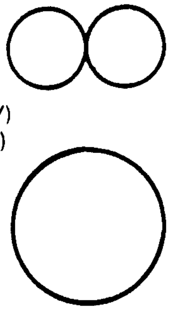
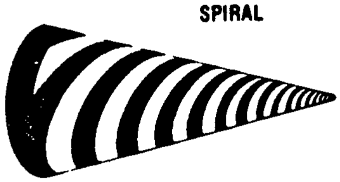
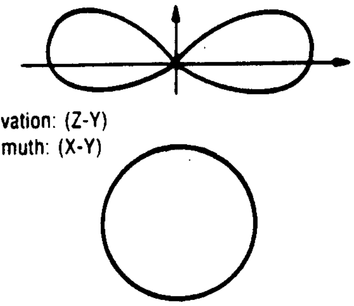
Antenna Type	Radiation Pattern	Specifications
YAGI 	 Elevation: (Z-Y) Azimuth: (X-Y)	**Polarization** Linear **Typical Half-Power Beamwidth** 50° x 50° **Typical Gain** 5 to 15 dB **Bandwidth** 5% **Frequency Limit** **Lower:** 50 MHz **Upper:** 2 GHz
DIPOLE ARRAY 	 Elevation: (Z-Y) Azimuth: (X-Y)	**Polarization** Linear **Typical Half-Power Beamwidth** 20° x 20° **Typical Gain** 5 to 30 dB **Bandwidth** 10% **Frequency Limit** **Lower:** 50 MHz **Upper:** 4 GHz
LOG PERIODIC 	 Elevation: (Z-Y) Azimuth: (X-Y)	**Polarization** Linear **Typical Half-Power Beamwidth** 60° x 80° **Typical Gain** 6 to 8 dB **Bandwidth** 10:1 **Frequency Limit** **Lower:** 3 MHz **Upper:** 18 GHz
HORN 	 Elevation: (Z-Y) Azimuth: (X-Y)	**Polarization** Linear **Typical Half-Power Beamwidth** 40° x 40° **Typical Gain** 5 to 20 dB **Bandwidth** 4:1 **Frequency Limit** **Lower:** 50 MHz **Upper:** 40 GHz

Table II. Antenna Characteristics

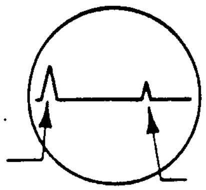
Antenna Type	Radiation Pattern	Specifications
NORMAL MODE HELIX 	 Elevation: (Z-Y) Azimuth: (X-Y)	**Polarization** Circular **Typical Half-Power Beamwidth** 60° x 360° **Typical Gain** 0 dB **Bandwidth** 5% **Frequency Limit** **Lower:** 100 MHz **Upper:** 3 GHz
BICONICAL WITH POLARIZER 	 Elevation: (Z-Y) Azimuth: (X-Y)	**Polarization** Circular **Typical Half-Power Beamwidth** 20°–100° x 360° **Typical Gain** 0 to 4 dB **Bandwidth** 3:1 **Frequency Limit** **Lower:** 2 GHz **Upper:** 18 GHz
LINDENBLAD 	 Elevation: (Z-Y) Azimuth: (X-Y)	**Polarization** Circular **Typical Half-Power Beamwidth** 80° x 360° **Typical Gain** −1 dB **Bandwidth** 2:1 **Frequency Limit** **Lower:** 100 MHz **Upper:** 12 GHz
4-ARM CONICAL SPIRAL 	 Elevation: (Z-Y) Azimuth: (X-Y)	**Polarization** Circular **Typical Half-Power Beamwidth** 50° x 360° **Typical Gain** 0 dB **Bandwidth** 4:1 **Frequency Limit** **Lower:** 500 MHz **Upper:** 18 GHz

Antenna Scan Characteristics

FIXED OR MANUALLY CONTROLLED SCAN

Note: In ALL of these drawings, the Side Lobes have been omitted for clarity.

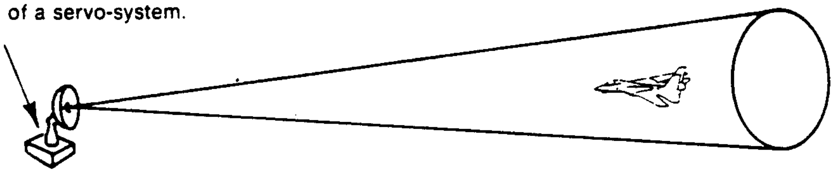
Typical Display



Zero Range
(Transmitter Pulse)

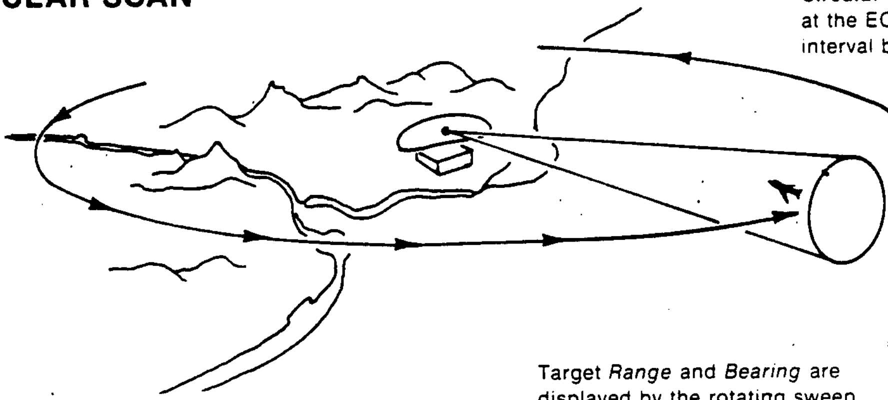
"A" Scope
Presentation gives
RANGE only

Antenna Azimuth may be read out from the mechanical positioning of the antenna by means of a servo-system.

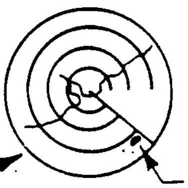


CIRCULAR SCAN

Circular Scan may be identified at the ECM Rec by its *regular* interval between illuminations.



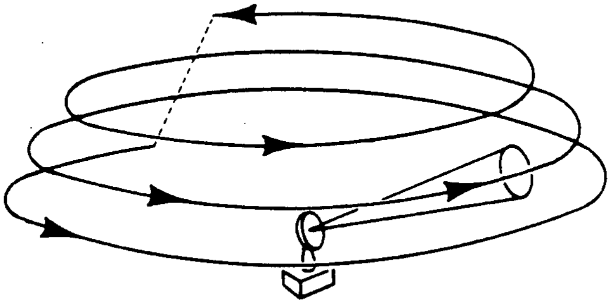
Target *Range* and *Bearing* are displayed by the rotating sweep in a map-like presentation. (PPI-Plan Position Indicator)



"PPI" Scope

HELICAL SCAN

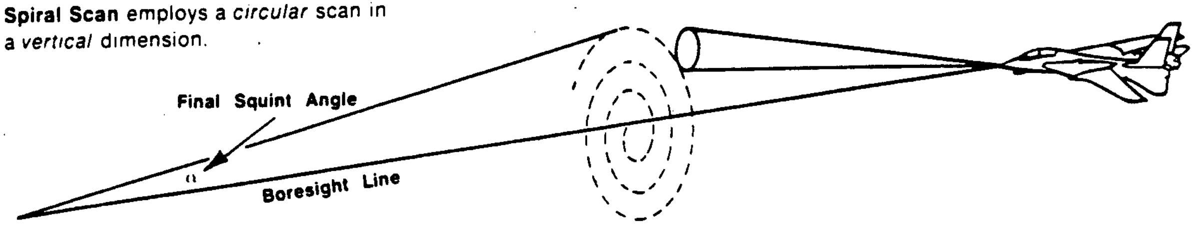
Typical Display
may be "PPI," possibly
with an "A" Scope as an
auxiliary presentation.



Courtesy of GTE Sylvania Inc., Electronic Systems Group
Western Division, Mountain View CA

SPIRAL SCAN

Spiral Scan employs a *circular* scan in a *vertical* dimension.

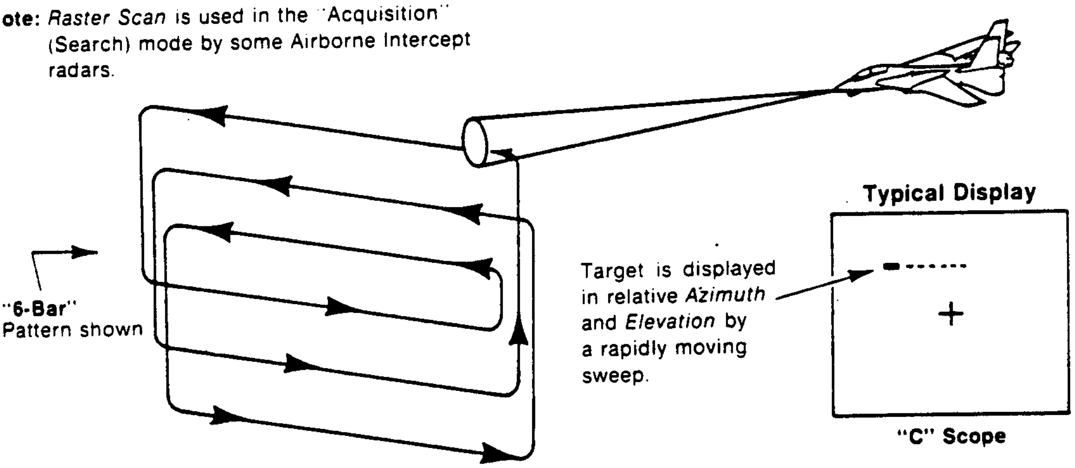


Provides *range* with relative *azimuth* and elevation.

Used as an acquisition mode of some threat radars.

RASTER SCAN

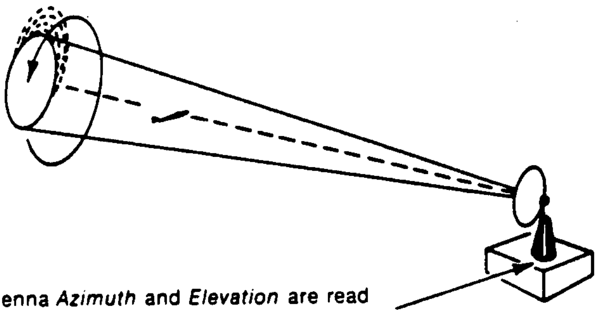
Note: *Raster Scan* is used in the "Acquisition" (Search) mode by some Airborne Intercept radars.



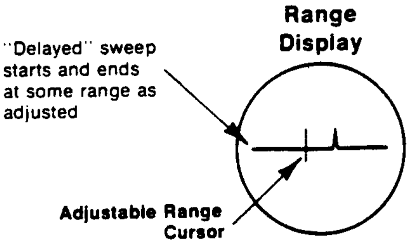
Target is displayed in relative *Azimuth* and *Elevation* by a rapidly moving sweep.

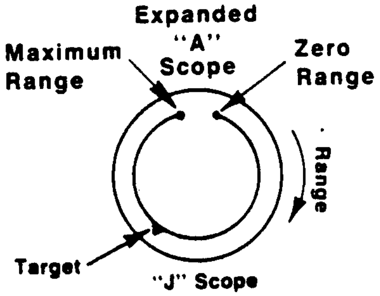
CONICAL SCAN

Note: Conical Scan is employed by some Automatic AA radars and Airborne Intercept radars.



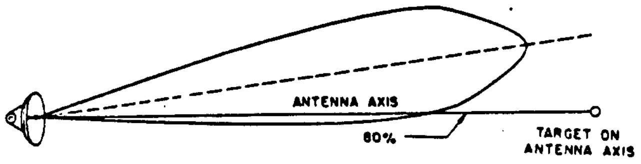
Antenna *Azimuth* and *Elevation* are read from the mechanical position of the dish, for inputs to the automatic tracking computer.



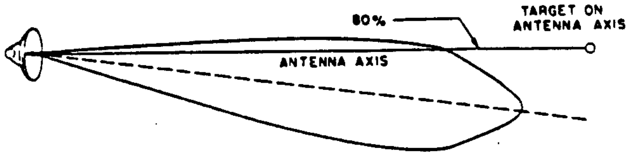


Antenna Scan Characteristics

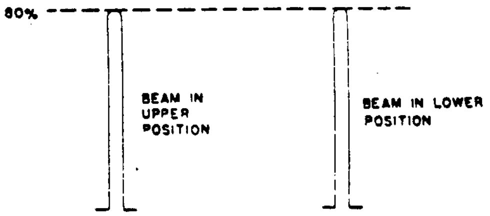
Echo Signals with Conical Scan



Beam in Upper Position

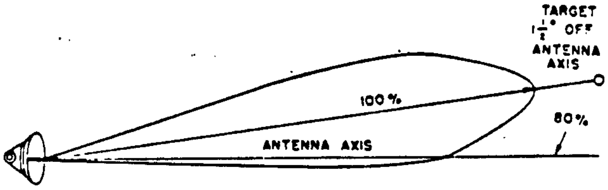


Beam in Lower Position

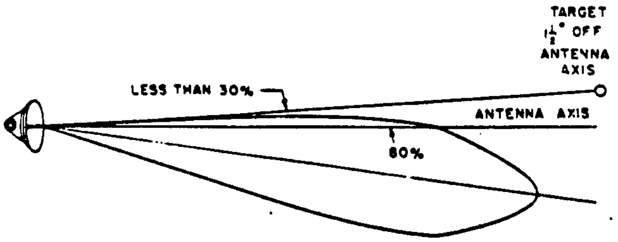


Return Signals from Target
1-1/2° Off Antenna Axis

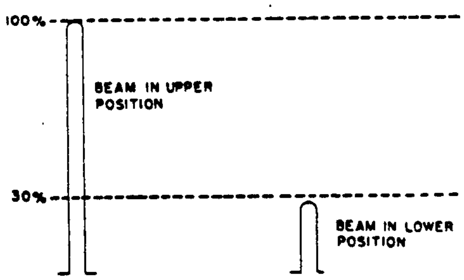
Echo Signals with Conical Scan



Beam in Upper Position

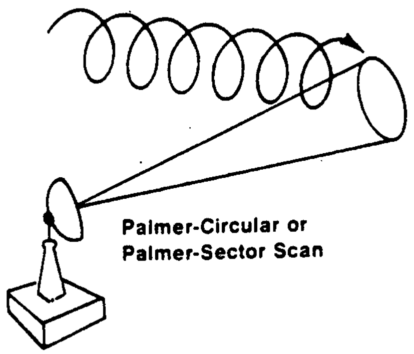


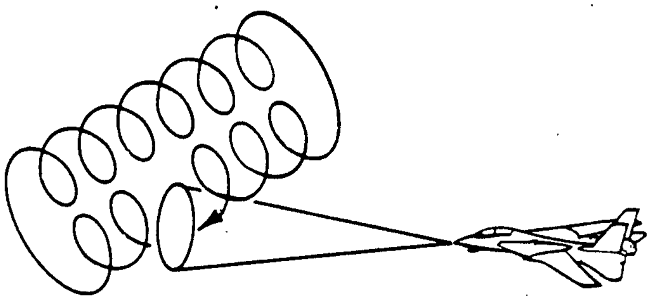
Beam in Lower Position



Return Signals from Target
on Antenna Axis

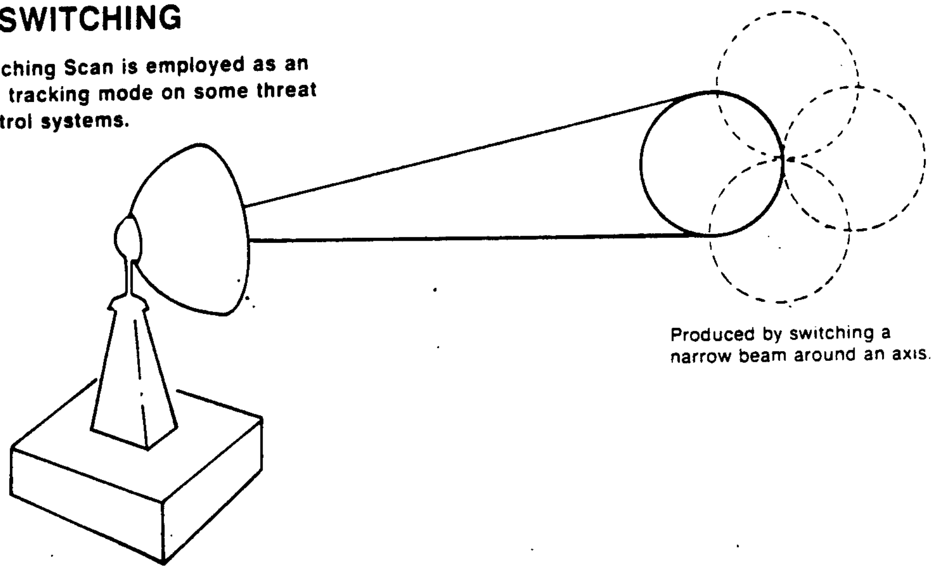
PALMER SCAN (Conical Scan superimposed on some other scan)


Palmer-Circular or Palmer-Sector Scan

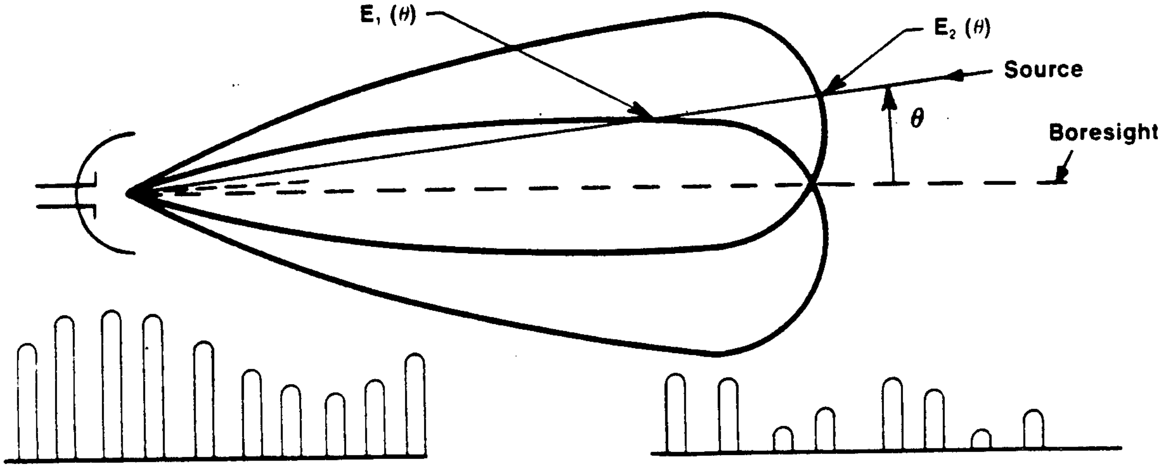

"2-Bar" Palmer-Raster Scan

LOBE-SWITCHING

Lobe-Switching Scan is employed as an automatic tracking mode on some threat radar control systems.

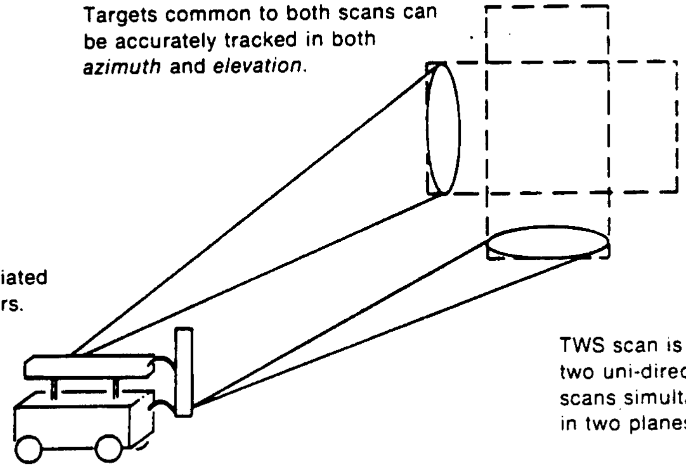

Produced by switching a narrow beam around an axis.

AMPLITUDE COMPARISON



Antenna Scan Characteristics

TRACK WHILE SCAN

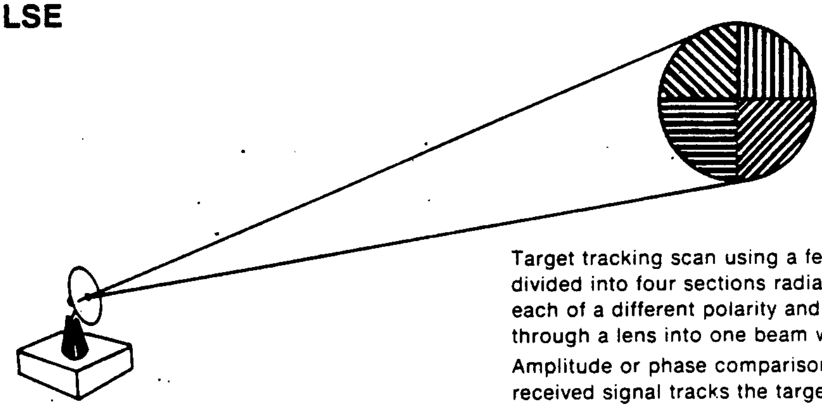


Targets common to both scans can be accurately tracked in both *azimuth* and *elevation*.

TWS is commonly associated with guided missile radars.

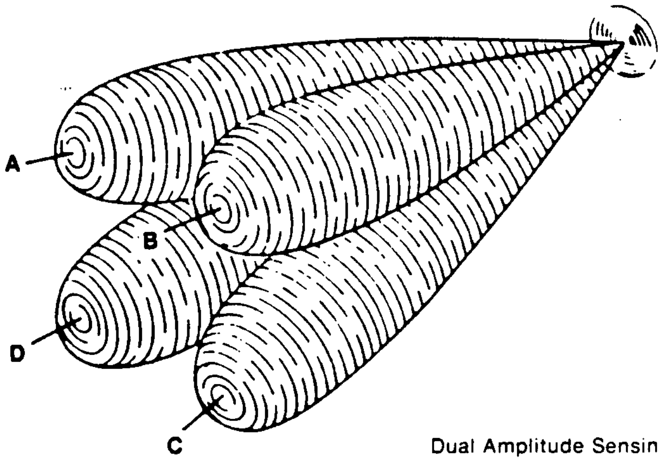
TWS scan is produced by two uni-directional sector scans simultaneously scanning in two planes.

MONOPULSE



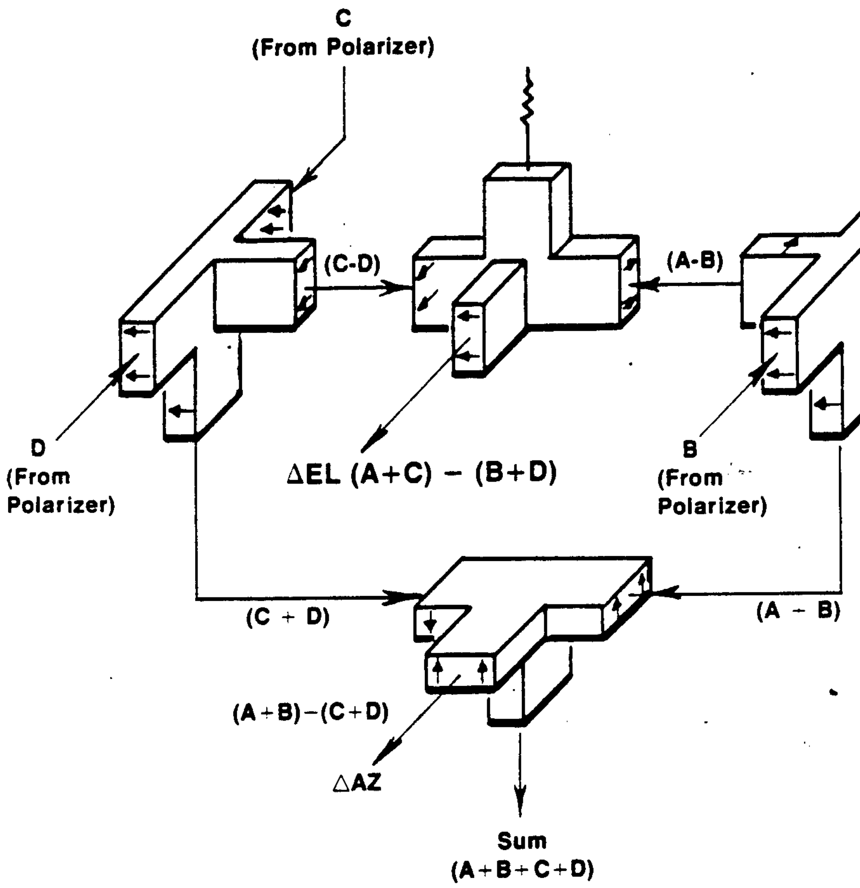
Target tracking scan using a feedhorn that is divided into four sections radiating four beams each of a different polarity and focused through a lens into one beam with four quadrants. Amplitude or phase comparison of the received signal tracks the target through space.

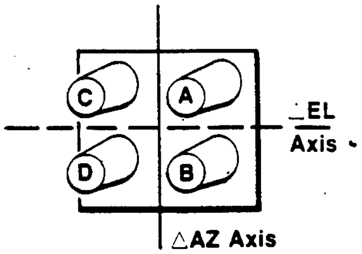
AMPLITUDE



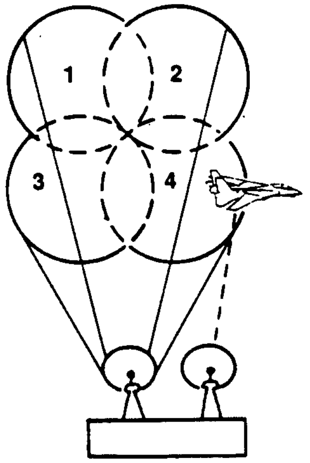
Dual Amplitude Sensing with Four Beams

SIGNAL FLOW IN THE MONOPULSE COMPARATOR





Antenna Elements



LORO

Lobe On Receive Only

Four beams transmitted simultaneously

separate receive antenna sampling the transmitted beams in a lobe switching pattern.

COSRO

COnical Scan on Receive Only

Four beams transmitted simultaneously.

separate receive antenna nutating the receive signal only giving a conical scan component to the radar receiver.

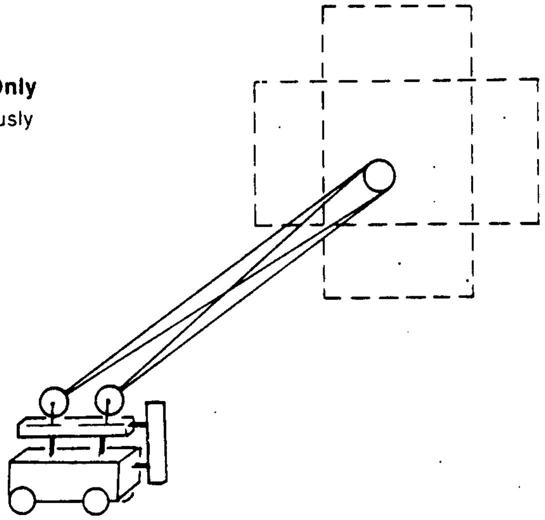
Antenna Scan Characteristics

TWSRO

Track While Scan on Receive Only

Two beams transmitted simultaneously to produce overlapping beams to illuminate the target area.

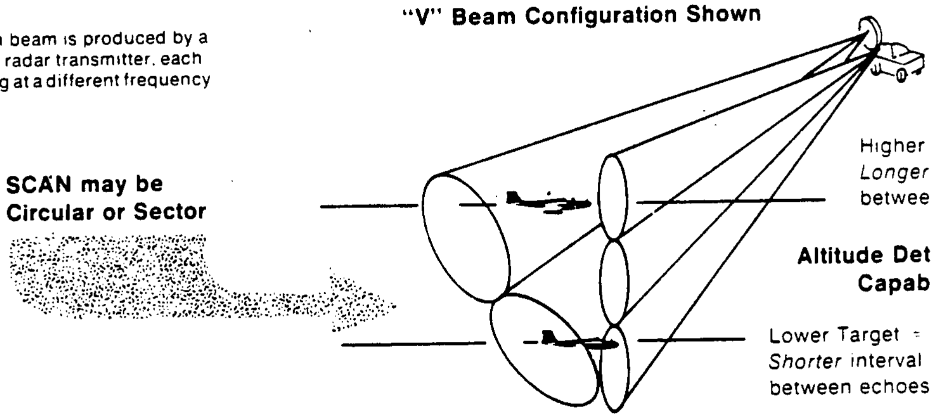
Two receive antennas employing uni-directional sector scans to scan the illuminated target area.



MULTI-BEAM RADAR

Note: Each beam is produced by a separate radar transmitter, each operating at a different frequency

"V" Beam Configuration Shown



SCAN may be Circular or Sector

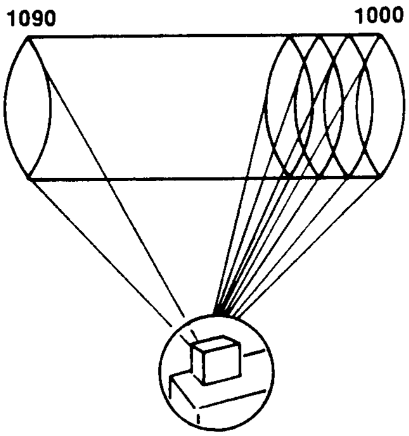
Higher Target
Longer interval
between echoes

Altitude Determining Capability

Lower Target =
Shorter interval
between echoes

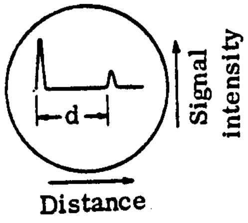
Typical Display may be either **"PPI"** or **"EPI"**

FRESCAN

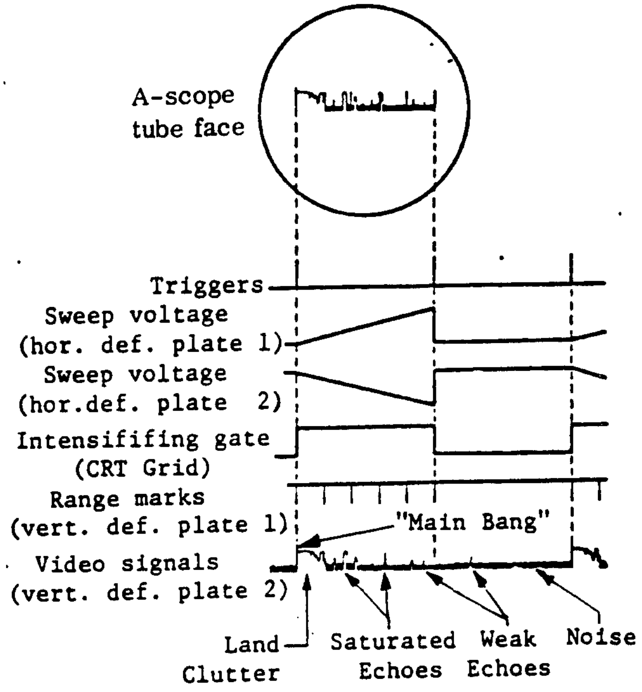


A uni-directional scan employing several RF frequencies: each RF beam overlaps previous beam. Uni-directional sector produced by changing radar frequency in discrete steps. Each step results in an overlapping beam. Each on a different bearing

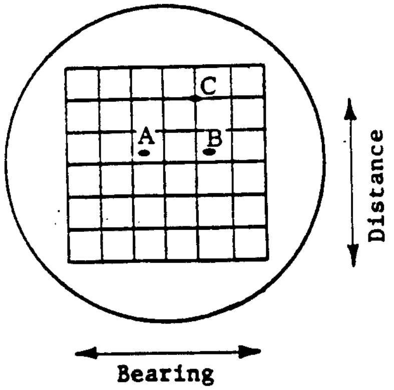
A-DISPLAY



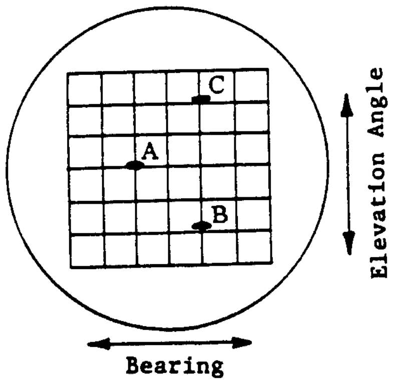
A-DISPLAY



B-DISPLAY

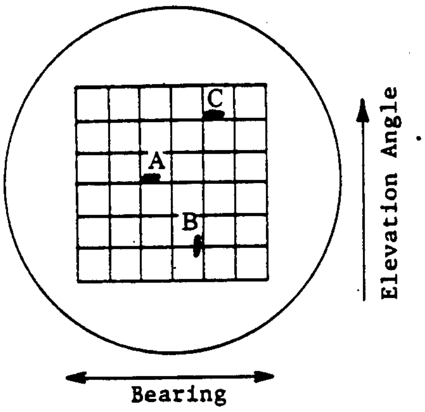


C-DISPLAY

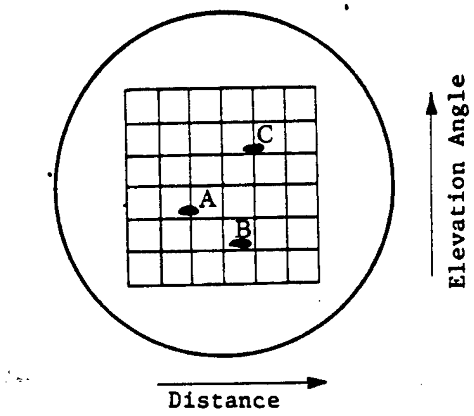


Antenna Scan Characteristics

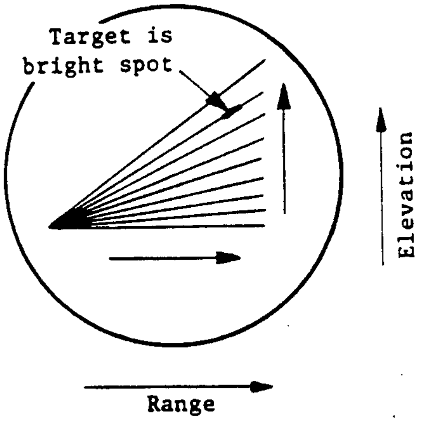
D-DISPLAY



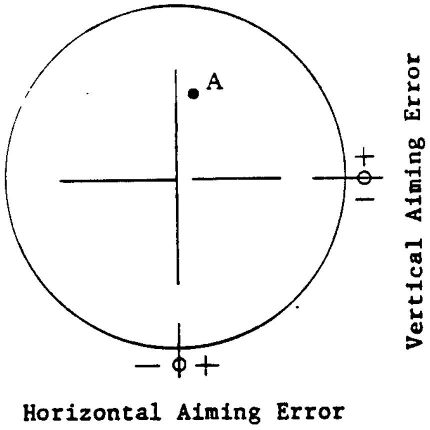
E-DISPLAY



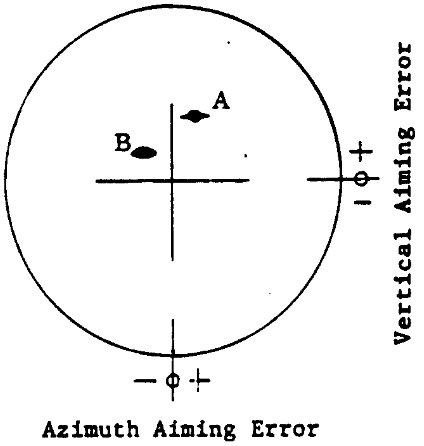
E SCAN



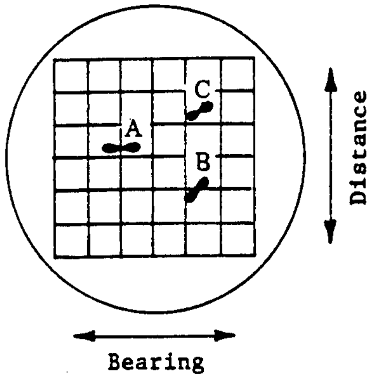
F-DISPLAY



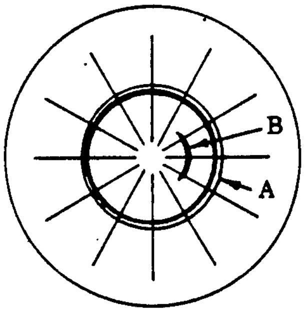
G-DISPLAY



H-DISPLAY

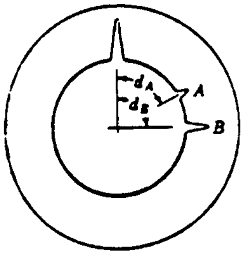


I-DISPLAY



Two targets (A,B) at different distances. Radar is aimed on target A.

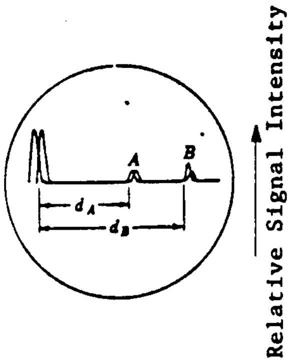
J-DISPLAY



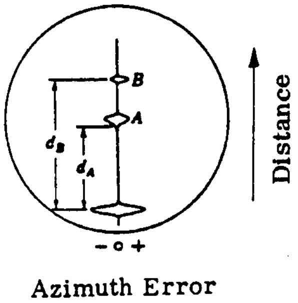
Two targets (A,B) at different distances.

Antenna Scan Characteristics

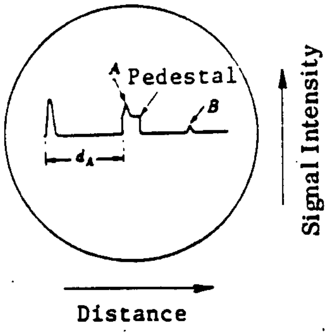
K-DISPLAY



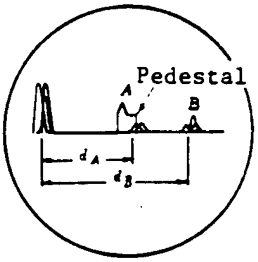
L-DISPLAY



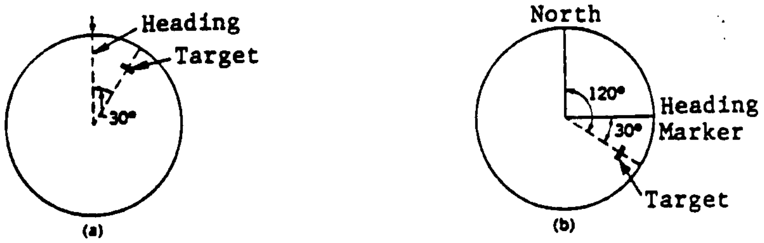
M-DISPLAY



N-DISPLAY



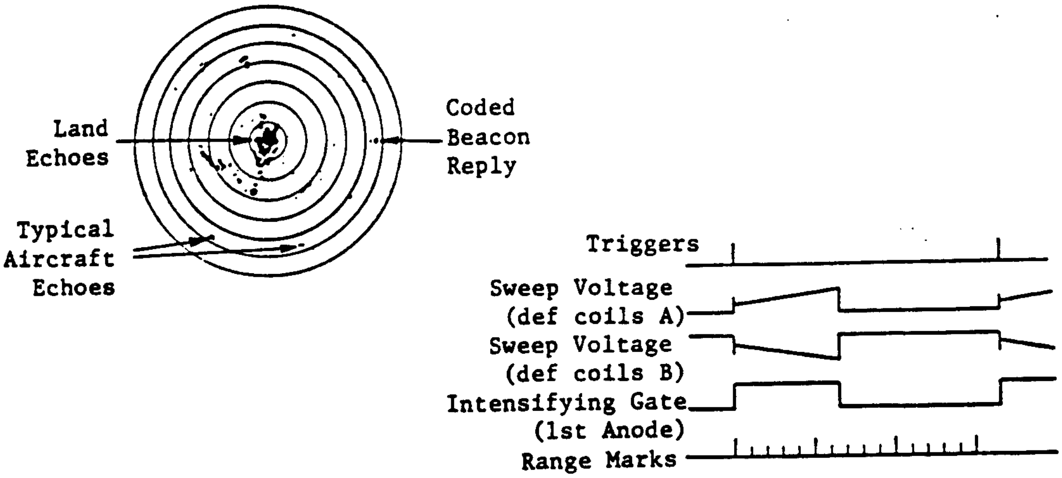
P-DISPLAY

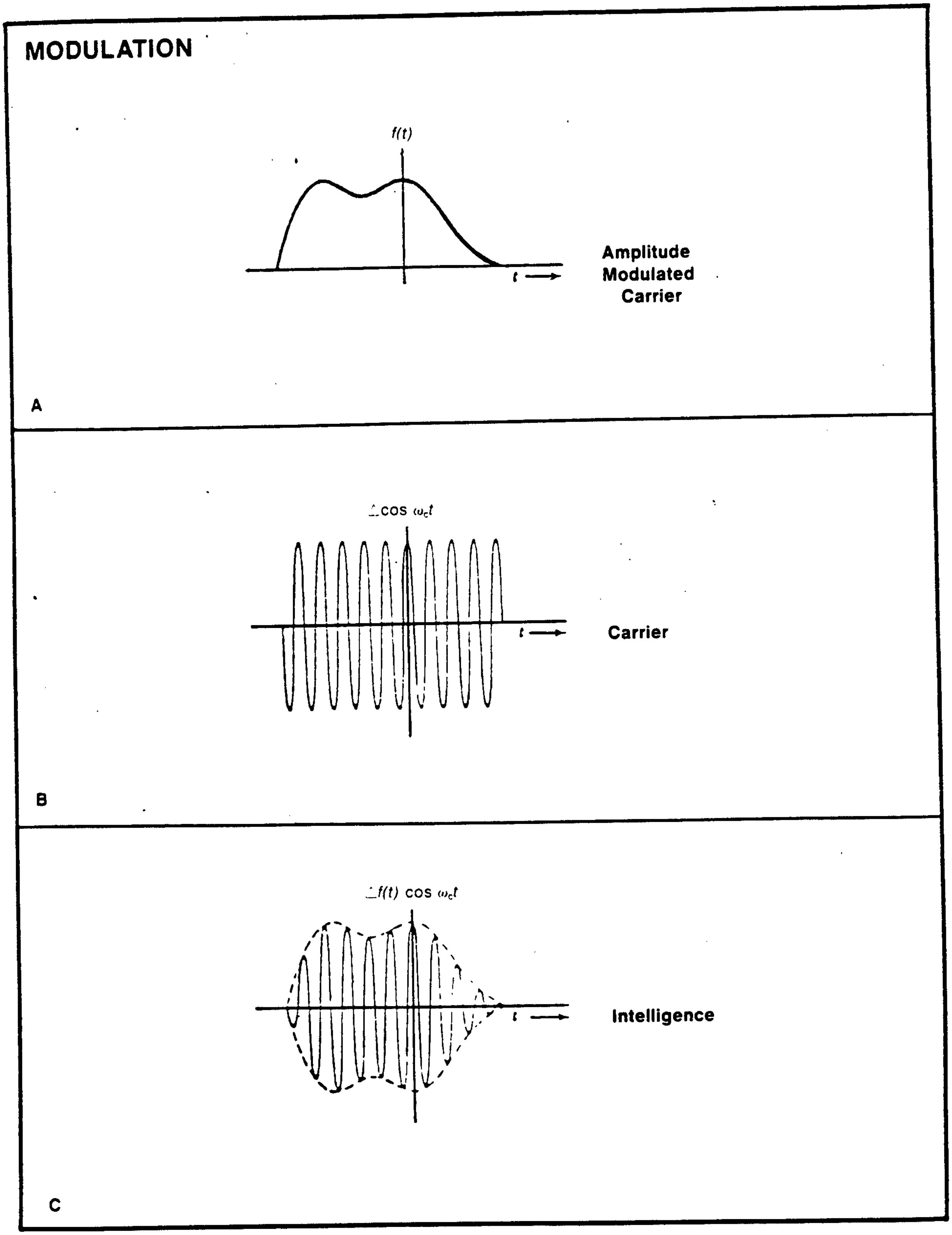


(a) (b)

P-DISPLAY

PPI tube face-sweep length 60mi
(video signals applied to the cathode)




MODULATION
$f(t)$
$t \longrightarrow$
Amplitude Modulated Carrier
A
$\pm\cos \omega_c t$
$t \longrightarrow$
Carrier
B
$\pm f(t) \cos \omega_c t$
$t \longrightarrow$
Intelligence
C

Glossary of Symbols, Terms and Abbreviations

Za = Antenna Impedance = $R_R + jX_a$
where: R_R = Antenna Radiation Resistance
X_a = Antenna Terminal Reactance

Radiation Resistance = That coefficient by which the square of the effective current on the antenna (I^2_{EFF}) can be multiplied to obtain the effective power radiated by the antenna.

Zo = Antenna Characteristic Impedance.

Radiation Pattern = A plot of the electric field strength in polar coordinates.

Polarization = The direction of the electric field vector with respect to a set of coordinate axes.

Linear Polarization = The direction of the resultant electric field vector is constant with time.

Vertical Polarization = Here taken to mean perpendicular to the earth surface or ground plane for the given orientation of the antenna.

Horizontal Polarization = Here taken to mean parallel to the earth's surface (or ground plane) for the given orientation of the antenna.

Circular Polarization = The direction of the resultant electric field vector varies with time in such a fashion that its tip traces out a circle in the plane perpendicular to the direction of propagation.

Resonant Antenna = One whose impedance is pure resistance.

Gain = Ratio of maximum radiation intensity in a given direction to the maximum radiation intensity produced in the same direction by a hypothetical lossless antenna which radiates uniformly in all directions (an isotropic radiator), for same power input.

Bandwidth = The frequency range over which the antenna impedance variation will not cause the standing wave ratio to exceed some specified limit, typically 1.5 to 2.

HPBW = **Half-Power Beamwidth** = The angular beamwidth in degrees of the radiated power pattern at the half-power point.

λ = Free space wavelength.

$\eta = 120\pi$

1n = Natural or Naperian logarithm.

VSWR = **Voltage Standing Wave Ratio** = Ratio of voltage maximum to voltage minimum of a standing wave pattern.

The angles θ and ϕ where used are measured in the usual way for standard spherical coordinates.

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Courtesy of Sylvania Electronic Systems Division of General Telephone & Electronics

ECM Techniques Glossary

Aerosols - solid particles dispersed in the atmosphere having resonant size particles with a high index of refraction. The particles both scatter and absorb visual and laser directed energy so as to cut down on weapon systems directed by these techniques.

Asynchronous Pulsed Jamming—where the jammer nearly matches the pulse repetition frequency (PRF) of the victim radar, and transmits multiples of the PRF.

Barrage Noise Jamming—noise jamming spread in frequency to deny the use of multiple radar frequencies to effectively deny range information.

Blinking -spot noise jamming by two sources in the same angular cell of the victim radar. The jamming is alternated between sources causing the radar system to oscillate back and forth. Too high a blinking frequency can allow the tracker to average the data while too low a frequency will cause the missile to home-in on one of the jammers.

Buddy Mode—multiple jamming aircraft in the same radar angular resolution cell. Potentially of use in jamming angle-tracking monopulse radars.

Cooperative Countermeasures—same concept as Buddy Mode, but requires communication between platforms. Generates larger errors

Countdown—a technique for forcing the radar AGC to continuously change value, and, hopefully even oscillate. The jammer rapidly changes the duty cycle of the deception pulses.

Cover Pulse jammer covers radar return with a pulse usually much wider than the radar pulse. Since tracking circuits are looking for largest return, they will transfer to the cover pulse, thereby denying range information.

Cross Eye - technique used against monopulse and other passive lobing radars. Jammer is a two-source interferometer that causes the phase front of the signal reaching the radar to be highly distorted, requires a high jam-to-signal ratio or the skin echo will show up in the pattern nulls.

Cross Polarization - or "Cross Pole", is a monopulse jamming technique where a cross-polarized signal is transmitted to give erroneous angle data to the radar. The component of the jamming signal with the same polarization as the radar must be very small.

Deception Jamming—any means of jamming consisting of false signals that have similar characteristics to the victim radar thereby deceiving the operator into erroneous conclusions.

False Target - typically used against search radars. Introduces pulse (targets) into the radar passband at times not corresponding to actual radar returns. Effect is to create a response at ranges where there is no target.

Image Jamming - Jamming the image frequency of a monopulse radar causing the antenna to be driven away from the target. Not effective if the radar uses image rejection.

Instantaneous Inverse Gain—pulse-by-pulse amplification, modulation and re-radiation of the victim radar's pulses to obscure angle data.

Inverse Gain—amplification, inverse modulation and re-radiation of a radar's pulse train at the nutation rate of the radar scan. Deceives a conical scanning radar in angle.

Obscuration—effects produced by masking-type jammers. Denial of either range or angle is achieved by submerging data in interference caused by noise or noise-like signals.

PRF Stripping—another name for countdown (see Countdown).

Range Gate Pull-In (RGPI)—same as range gate pull-off (see next entry) except that the deceptive pulse is transmitted before the radar pulse is received. This is accomplished by digital storage of the pulse repetition period, which must be extremely stable.

Range Gate Pull Off (RGPO)—deception technique used against pulse tracking radars using range gates. Jammer initially repeats the skin echo with minimum time delay at a high power to capture the AGC circuitry. The delay is progressively increased, forcing the tracking gates to be pulled away ("walked off") from the skin echo. Frequency memory loops (FML's), or transponders provide the variable delay.

Repeater Jamming—any equipment that intercepts and re-radiates a modified signal to present erroneous data on azimuth, range, number of targets, etc.

Skirt Frequency Jamming—jamming a monopulse radar at frequencies on the skirts of the response curve of the radar. Careful radar design minimizes the effectiveness of this technique.

Smith Modulation—deceptive technique which operates on the servo loop of the victim radar. Two RF carriers are transmitted with a few cycles difference.

Spot Noise Jamming—jammer's entire power output is concentrated in a very narrow bandwidth, ideally identical to that of the victim radar. Used to deny range and sometimes angle information.

Sweep Lock Jamming—a swept jammer with an additional feature of lock-on capability.

Swept Audio—jamming technique usually employed against conical-scan-on-receive-only (COSRO) radars. The received pulses are amplified and re-transmitted by the target and are amplitude modulated at a frequency close to the suspected receiver antenna scan frequency.

Serrodyne—a method of "pulling-off" the velocity gate of a doppler radar by using a voltage-controlled phase shifter, using a Traveling Wave Tube (TWT). This introduces a frequency shift from zero to some maximum value, pulling the doppler tracking gate away from the skin echo. The phase shift is usually accomplished by modulating the TWT's helix voltages.

Transponder—device used to transmit jamming pulses at the frequency of the victim radar by use of an internal oscillator. Used for cover pulses, RGPO, RGPI and false targets.

Velocity Gate Pull-Off (VGPO)—method of capturing the velocity gate of a doppler radar and moving it away from the skin echo.

Fundamental Jamming Relationships

There are a number of calculations that need to be made in connection with jamming. For example, how much power is required from a jammer to screen a given target if the jammer is carried on the target? If the jammer is carried on a separate vehicle (stand-off jammer)? How much gain is required in a deceptive repeater to simulate a given size target? Given jammer and target characteristics, what is the minimum range at which the target will be protected?

In free space the radar echo power returned from a target varies inversely as the fourth power of the range, while power received at the radar from a jammer carried on the target varies inversely with the square of the target range. Therefore, as range decreases, radar echo power increases more rapidly than does received energy from the jammer. Inevitably a point is reached where the energy received from a noise jammer is no longer great enough to hide the skin echo. This range is called the burn-through range.

The Self Protection Jammer. The received radar signal power can be written as

$$S = \frac{P_r G_r^2 \sigma \lambda^2 g^4}{(4\pi)^3 R^4} \qquad (1)$$

where S = received echo signal power
P_r = radar power output
G_r = gain of radar antenna toward target
σ = target radar cross section
λ = wavelength
R = radar-to-target range
g^2 = propagation one-way power gain; $0 \leqslant g^2 \leqslant 4$

Due to reflections from the earth, the signal field strength at the target may be anywhere from 0 (reflected and direct rays cancel) to two times (reflected and direct rays are equal and additive) the strength the field would have in free space. The ratio of field strength to free-space. The ratio of field strength to free-space field strength is g. Power is proportional to the square of the field strength, or to g^2. The propagation factor in the equation is for two-way propagation, hence g^4. In calculating the magnitude of the propagation factor, the effects of atmospheric attenuation should be included.

The jamming energy received by the radar within the receiver bandwidth, J, can be given by

$$J = \frac{P_j B G_j G_r \lambda^2 g^2}{(4\pi)^2 R^2} \qquad (2)$$

where P_j = jammer power output per unit bandwidth
B = radar receiver noise bandwidth
G_j = gain of jammer antenna toward radar

The jammer bandwidth is generally greater than the radar receiver bandwidth; hence, only a fraction of the jammer power output is effective in jamming the radar.

By combining equations (1) and (2), the equation for the jam-to-signal ratio, J/S, is

$$\frac{J}{S} = \frac{4\pi P_j G_j B R^2}{P_r G_r \sigma g^2} \qquad (3)$$

By replacing J/S by C, the minimum J/S ratio for which the target is obscured, equation (3) can be solved for burn-through range, the minimum target range at which the target is obscured. C is called the camouflage factor.

$$R_B = \sqrt{\frac{P_r G_r C \sigma g^2}{4\pi P_j G_j B}} \qquad (4)$$

If the jammer noise as received has the same characteristics as receiver noise, then the camouflage factor is the reciprocal of the minimum signal-to-noise ratio for detection. Thus if a radar has a signal processing that permits the detection of targets with a minimum signal-to-noise ratio of 0.5, then a camouflage factor of 2 will be required to obscure the target.

The Stand-Off Jammer. Frequently jammers are carried on escort vehicles rather than on the platform to be protected. The escort vehicles in this case frequently stand off at a distance from the target, out of range of the target defenses.

The stand-off jamming equation may be derived by first modifying slightly equations (1) and (2). In equation (1), R is replaced by R_t, the radar-to-target range, and g is replaced by g_t, the radar-to-target propagation factor. In equation (2), G_j is replaced by G_{jr}, the gain of the jammer antenna toward the radar; R by R_j, the radar-to-jammer range; and g by g_j, the propagation factor on the jammer-to-radar path. It follows that

$$\frac{J}{S} = \frac{4\pi P_j B G_{jr} G_{rj}}{P_r G_r^2 \sigma} \, \frac{R_t^4}{R_j^2} \, \frac{g_j^2}{g_t^4} \qquad (5)$$

and

$$R_B = \sqrt[4]{\frac{P_r G_r^2 C \sigma R_j^2}{4\pi P_j B G_{jr} G_{rj}} \, \frac{g_t^4}{g_j^2}} \qquad (6)$$

Repeater Gain Requirement. A repeater receives a signal, amplifies it, and retransmits it either with or without additional modulation. An unmodulated repeater may be used to make the radar target appear larger than it really is, a decoy. A modulated repeater may also be used for break lock of a tracking radar.

FUNDAMENTAL JAMMING RELATIONSHIPS

To calculate the gain required of a repeater, first write an equation for the power reflected from the target, P_{refl}:

$$P_{refl} = \frac{P_r G_r \sigma g^2}{4\pi R^2}$$

The power radiated by the repeater toward the radar is given by

$$P_j = \frac{P_r G_r G_{jr} G_{jt} G_e \lambda^2 g^2}{(4\pi)^2 R^2}$$

where G_e = gain of repeater (electronic gain). The jam-to-signal ratio then is

$$\frac{J}{S} = \frac{G_{jr} G_{jt} G_e \lambda^2}{4\pi\sigma} \tag{7}$$

Note that the J/S ratio is independent of range. Replacing J/S by C and solving for the product of the three gains,

$$G_{jr} G_{jt} G_e = \frac{4\pi C\sigma}{\lambda^2} \tag{8}$$

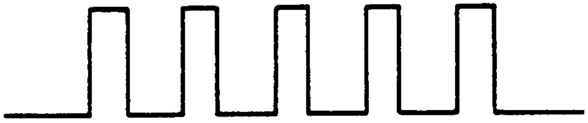
$C\sigma$ is the additional radar cross section simulated by the repeater, σ.

$$G_{jr} G_{jt} G_e = \frac{4\pi\ \sigma_s}{\lambda^2}$$

The Modulated Repeater. The equations developed above for the required repeater gain assume that the repeater is unmodulated, and hence its output signal bandwidth is the same as the bandwidth of the radar signal. If the repeater is modulated, its bandwidth is increased. If the increase is substantial, part of the radiated energy lies outside the radar receiver pass band. The repeater gain must then be increased to compensate for this loss of signal energy.

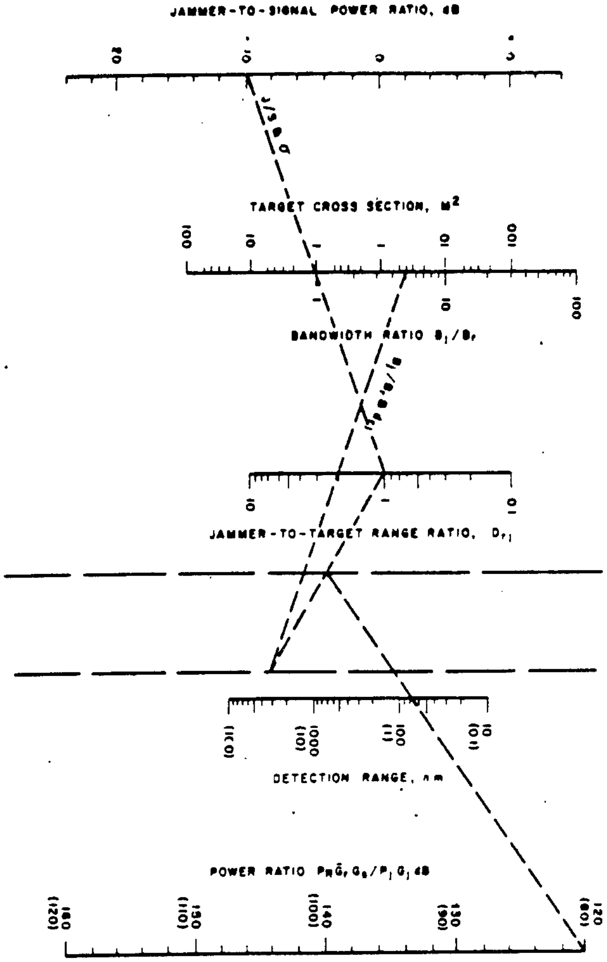
A common type of repeater is the gated repeater which is turned on and off from one to several times during a repeated pulse in order to avoid feedback from the transmitting to the receiving antenna, as shown in Figure 1. Note the DC component of the pulse envelope voltage is reduced by the factor β, where β is the duty cycle. It follows that the carrier power output is reduced by β^2. The gain of the gated repeater must be increased by $1/\beta^2$ to compensate for the loss due to gating. For the gated repeater then

a. Radar pulse envelope



b. Repeater output envelope

Gated repeater operation



$$G_{jr} G_{jt} G_e = \frac{4\pi\ C\sigma}{\beta^2 \lambda^2} \tag{9}$$

Repeater Power Output. Repeater gain remains constant as long as its amplifier does not saturate. The repeater power output therefore increases as range decreases. If the range is decreased arbitrarily close to zero, the repeater must eventually saturate.

It is instructive to calculate repeater output power as a function of range. The input power is given by

$$P_{in} = \frac{P_r G_r g^2}{4\pi R^2} A_e = \frac{P_r G_r G_{jr} \lambda^2 g^2}{(4\pi R)^2} \tag{10}$$

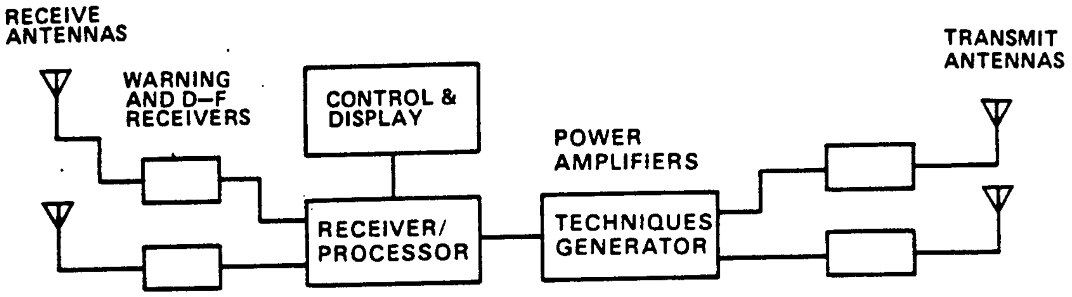
Solving equation (9) for the electronic gain and multiplying by P_{in},

$$P_{out} = \frac{P_r G_r \sigma_s g^2}{4\pi R^2 G_{jt} \beta^2} \tag{11}$$

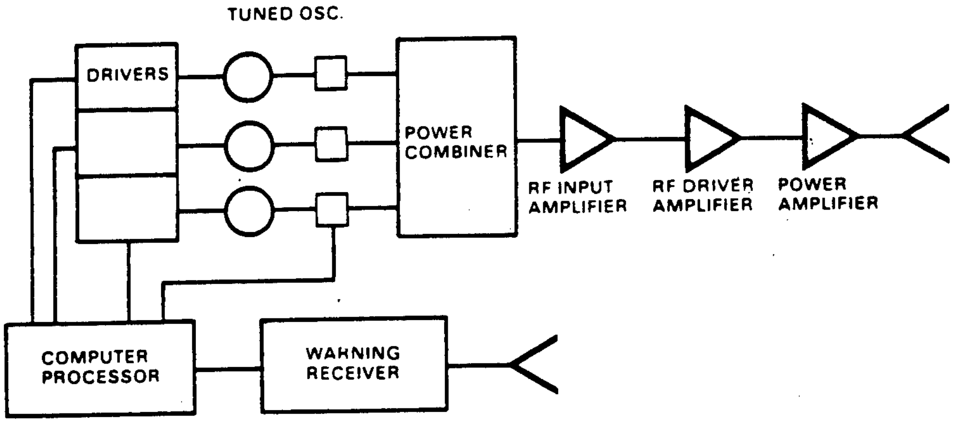
If, in equation (11), the smallest range at which the repeater must be fully effective is used, the equation gives the required maximum power output.

FUNDAMENTAL JAMMING RELATIONSHIPS

Typical Pulse Repeater Deceptive Jamming System



Typical CW Noise Jamming System



Jamming Techniques by Radar Type

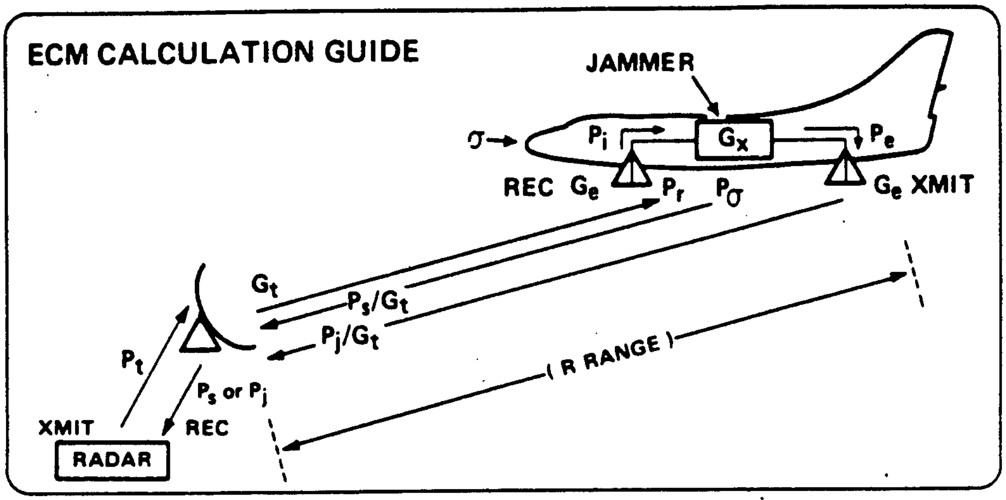
TRACKING RADAR TYPE	JAMMING TECHNIQUE	JAM-TO-SIGNAL RATIO REQUIRED (JSRR)	RECEIVER SENSITIVITY INCREASE REQUIRED (RSIR)	COMMENTS
PULSED	Noise	~0-6 dB	0 dB	
	RGPO Range Gate Pull Off	0-6 dB	0 dB	Technique usually used to pull radar off target signal and provide infinite jam-to-signal ratio for angle jamming techniques. JSRR varies with split or contiguous tracking gates, gate widths, gate separation, tracking servo response, pull-off rates of jammer. Relatively ineffective technique against manual operator
	RGPI/RGPO RANRAP	~0 dB	0 dB	Technique requires predictive gates. More effective against manual operator. However, requires more duty cycle from jammer
	COVER PULSE, also useful against leading edge tracking ECCM	~0 dB	0 dB	Technique useful to supply noise type response (defeat radars range resolution capability for techniques like Buddy Mode.)

FUNDAMENTAL JAMMING RELATIONSHIPS

TRACKING RADAR TYPE	JAMMING TECHNIQUE	JAM-TO-SIGNAL RATIO REQUIRED (JSRR)	RECEIVER SENSITIVITY INCREASE REQUIRED (RSIR)	COMMENTS
CW RADARS	VGPO replaces RGPO velocity gate	0-6 dB	0 dB	Technique usually used to pull radar off the target signal and provide infinite JSRR for angle jamming techniques
PULSE DOPPLER	VGPO combines with RGPO	0-6 dB	0 dB	Technique usually used to pull radar off the target signal and provide infinite JSRR for angle jamming techniques
PULSE CODED RADARS Chirp, etc	Frequency Time Ambiguity Jamming			JSRR dependent upon ambiguity diagrams and coding of signal
Angle Tracking Conical Scan or Active Lobe Switching	Inverse Gain Scan	10-25 dB for break lock	10-15 dB for break lock	JSRR & RSIR vary with squint angle and radar angle tracking time constants
TWS Auto Radar Track Track while scan	Main Lobe Blanking	10-15 dB	10 dB	JSRR for breaklock varies with angle tracking gate widths, gate separation, and tracking time constants
TWS Manual Radar Track	JETS	10-13 dB	10 dB	JSRR & effectiveness vary greatly with each specific operator
	Instantaneous Inverse Gain	~20 dB	~20 dB	JSRR & RSIR depend upon depth of radar nulls and the desired angular width of the jamming signal
TWSRO Track while scan receive only	JETS	10-13 dB	10 dB	JSRR for breaklock varies with angle tracking gate widths, gate separation, and time constants
COSRO	Swept Audio or Multiplexed Swept Audio	10-25 dB	10-15 dB	See CONSCAN & the sweep rate of the audio
	Above, with jog detection	10-25 dB	10-15 dB	These techniques are used to reduce uncertainty of threat scan rate PSD places strigent added requirements on signal processing
	Passive Scan Detection (PSD)	10-25 dB	10-15 dB	
Monopulse & other passive lobing radars with CAM	Cross-Polarization	20-40 dB	20-40 dB	JSRR & RSIR vary with Condon Lobe (Cross-Polarized) response of victim antenna The Condon Lobe response varies with F D ratio type of feedhorn illumination taper, and use of polarization screening
	Cross-Eye	~20 dB at 80' spacing at 20 NM at 1 0° BW threat antenna	~ 20 dB	JSRR & RSIR varies with antenna separation on aircraft in radar angular mils To jam at maximum range requires maximum JSRR
	Buddy Mode Radar Angular Resolution Cell Jamming	0-3 dB	10 dB	JSRR will vary significantly only if A C spacing exceed 1 radar beamwidth Requires multiple A C
	Cooperative Counter-measures	0-3 dB	10 dB	Same approximate requirements as Buddy Mode but requires communication amongst aircraft for technique coordination Generates larger errors
	Countdown	10-30 dB	10 dB	JSRR varies with AGC time constants and receiver instantaneous dynamic range
Range and or Velocity				RGPO etc and VGPO may be used in combination with any of the Angle Techniques
ALTERNATE LINKS	MISSILE BEACON TRACKING	0-6 dB	Requires a C D band receiver	JSRR quoted here will work but requires new definition from other JSRR s quoted and must be carefully implemented Technique is effective against command guidance missile systems that use radar to track a beacon in the missile and is effective countermeasure to *optical target track*

— JAMMING NOTES —

FUNDAMENTAL JAMMING RELATIONSHIPS



$P_i = \dfrac{P_t G_t G_e \lambda^2}{R^2 16\pi^2}$	RADAR POWER AT JAMMER INPUT
$P_s = \dfrac{P_t G_t^2 \lambda^2 \sigma}{R^4 16\pi^2 4\pi}$	RADAR SIGNAL POWER AT RADAR REC
$P_{j/s}\Big\vert_{P_e} = \dfrac{P_e G_e 4\pi R^2}{P_t G_t \sigma}$	JAM-SIGNAL RATIO AT RADAR FOR SATURATED JAMMER OUTPUT
$P_{j/s}\Big\vert_{G_x} = \dfrac{G_e^2 G_x \lambda^2}{4\pi\sigma}$	JAM-SIGNAL RATIO AT RADAR FOR UNSATURATED JAMMER OUTPUT (AND SELECTED JAMMER GAIN)
$R_e^2\Big\vert_{P_e} = \dfrac{P_t G_t G_e G_x \lambda^2}{P_e 16\pi^2}$	JAMMER SATURATION RANGE
$R_x^2\Big\vert_{P_{j/s}} = \dfrac{P_t G_t \sigma P_{j/s}}{P_e G_e 4\pi}$	JAM-SIGNAL CROSSOVER RANGE FOR SELECTED $P_{j/s}$
$P_{i(min)} = \dfrac{G_e \lambda}{2}\sqrt{\dfrac{P_{s(min)} P_t}{\pi\sigma}}$	MINIMUM RADAR POWER AT JAMMER RECEIVER AT THRESHOLD OF RADAR DETECTION
$P_{i(max)}\Big\vert_{P_{j/s}} = \dfrac{P_e G_e^2 \lambda^2}{4\pi\sigma P_{j/s}}$	MAXIMUM RADAR POWER AT JAMMER RECEIVER FOR SELECTED $P_{j/s}$ BURN THRU

P_t = POWER OF RADAR IN mW (DBM)

G_t = GAIN OF RADAR ANT. IN DB

G_e = GAIN OF JAMMER (REC. & XMIT) ANT'S. IN DB

P_i = RADAR POWER @ JAMMER INPUT IN mW(DBM)

λ = RF WAVELENGTH (METERS) IN DBM

P_s = RADAR REC. POWER FROM TARGET IN mW (DBM)

P_j = RADAR REC. POWER FROM JAMMER IN mW(DBM)

σ = RADAR TARGET REFERENCED TO 1 SQ. METER (DBM^2)

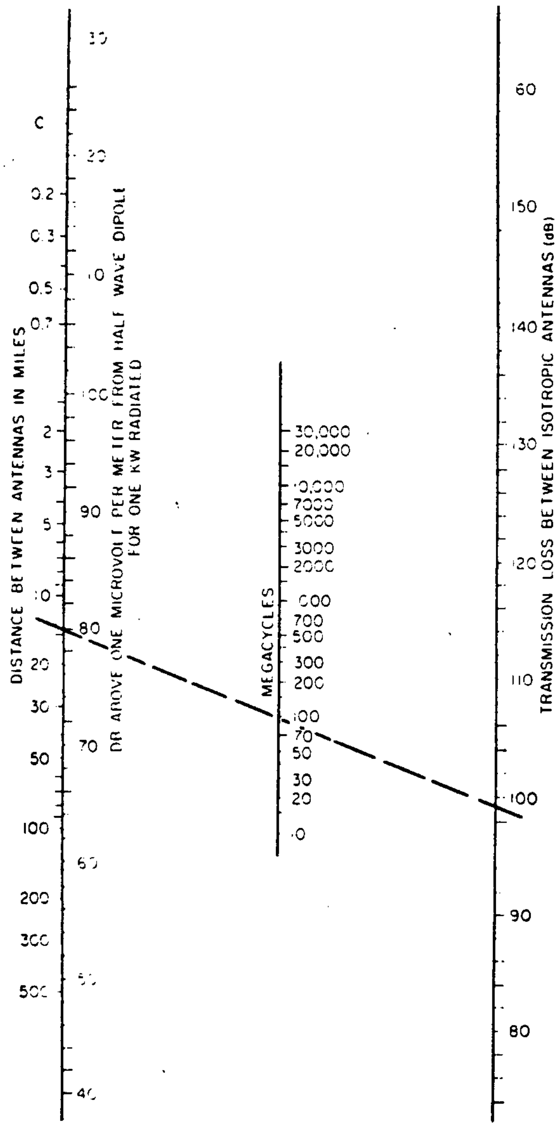
G_x = GAIN OF XPONDER RF AMP. IN DB

$P_{j/s}$ = JAMMER TO RADAR REC. POWER IN DB

R = RADAR RANGE IN METERS (DBM)

P_e = JAMMER OUT SATURATED POWER REFERENCED TO 1 mW(DBM)

Free space one way transmission loss between isotropic antennas.



Free Space, one way, transmission loss between Isotropic antennas.

The basic concept in estimating radio transmission loss is the loss expected in free space, that is, in a region free of all objects that might absorb or reflect radio energy. This concept is essentially the inverse square law in optics applied to radio transmission. For a one-wavelength separation between nondirective (isotropic) antennas, the free-space loss is 22 db, and it increases by 6 db each time the distance is doubled. The free-space transmission ratio at a distance *d* is given by

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi d}\right)^2 g_t g_r$$

where P_r, P_t = received power and radiated power, respectively, measured in same units
λ = wavelength, in same units as *d*
g_t (or g_r) = power gain of transmitting (or receiving) antenna

The power gain of an ideal isotropic antenna that radiates power uniformly in all directions is unity by definition.

Another form of expressing free-space transmission is the concept of the free-space field intensity E_0, which is given by

$$E_0 = \frac{\sqrt{30 P_t g_t}}{d} \quad \text{Volts/meter}$$

where *d* is in meters and P_t in watts.

The use of the field-intensity concept is frequently more convenient than the transmission-loss concept at frequencies below about 30 Mc, where external noise is generally controlling and where antenna dimensions and heights are comparable to or less than a wavelength. The free-space field intensity is independent of frequency, and its magnitude for 1 kw radiated from a half-wave dipole is shown on the left-hand scale of the nomograph.

The concept of free-space transmission assumes that the atmosphere is perfectly uniform and nonabsorbing and that the earth is either infinitely far away or its reflection coefficient is negligible. In practice, the modifying effects of the earth, the atmosphere, and the ionosphere need to be considered. The following nomographs take such factors into consideration.

Excerpted from Antenna Enginnering Handbook by Jasik with permission of the publisher, McGraw-Hill Book Co., Inc.

One Way Transmission Loss Between Isotropic Antennas Over Plane Earth.

The presence of the ground modifies the generation and the propagation of radio waves so that the received power or field intensity is ordinarily less than would be expected in free space. The effect of plane earth on the propagation of radio waves is given by

$$\frac{E}{E_0} = \underbrace{1}_{\text{Direct wave}} + \underbrace{Re^{j\Delta}}_{\text{Reflected waves}} + \underbrace{(1-R)Ae^{j\Delta}}_{\text{"Surface wave"}} + \underbrace{\cdots}_{\text{Induction field and secondary effects of the ground}}$$

where R = reflection coefficient of ground
A = "surface-wave" attenuation factor
$\Delta = \dfrac{4\pi h_1 h_2}{\lambda d}$
$h_{1,2}$ = antenna heights measured in same units as wavelength and distance

The parameters R and A depend to some extent on polarization and ground constants. The term "surface wave" has led to considerable confusion since it has been used in the literature to stand for entirely different concepts. However, the important point to note is that considerable simplification is possible in most practical cases and that the variations with polarization and ground constants and the confusion about the surface wave can often be neglected. For near-grazing paths, R is approximately equal to -1 and the factor A can be neglected as long as both antennas are elevated more than a wavelength above the ground (or more than 5 to 10 wavelengths above sea water). Under these conditions the effect of the earth is independent of polarization and ground constants and the above equation reduces to

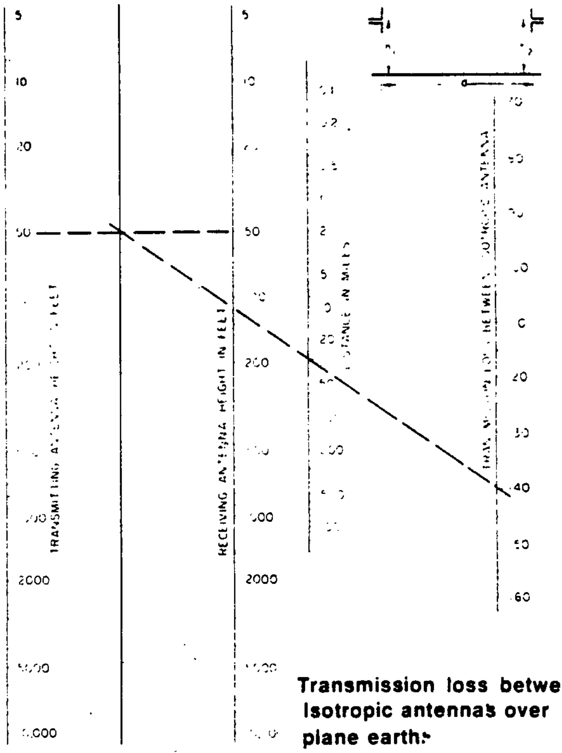
$$\left|\frac{E}{E_0}\right| = \sqrt{\frac{P_r}{P_0}} = 2\sin\frac{\Delta}{2} = 2\sin\frac{2\pi h_1 h_2}{\lambda d}$$

where P_0 is the received power expected in free space.

This expression is the sum of the direct and ground reflected rays and shows the lobe structure of the signal as it oscillates around the free-space value. In most radio applications (except air to ground) the principal interest is in the lower part of the first lobe, that is, where $\Delta/2 < \pi/4$. In this case, $\sin \Delta/2 \approx \Delta/2$, and the transmission loss over plane earth is given by

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi d}\right)^2 \left(\frac{4\pi h_1 h_2}{\lambda d}\right)^2 g_t g_r$$
$$= \left(\frac{h_1 h_2}{d^2}\right)^2 g_t g_r$$

It will be noted that this relation is independent of frequency, and it is shown in decibels for isotropic antennas. This nomograph is not valid when the indicated transmission loss is less than the free-space loss shown in the preceding nomograph for free space transmission loss, because this means that Δ is too large for this approximation.



Transmission loss between Isotropic antennas over plane earth.

Notes:
1. This chart is not valid when the indicated received power is greater than the free space power shown in the preceding nomograph for free space transmission loss.
2. Use the actual antenna height or the minimum effective height shown in the minimum effective antenna height chart, whichever is the larger.

Although the transmission loss shown in the nomograph has been derived from optical concepts that are not strictly valid for antenna heights less than a few wavelengths, approximate results can be obtained for lower heights by using h_1 (or h_2) as the larger of either the actual antenna height or the minimum effective antenna height (see chart on minimum effective antenna gain). The error that can result from the use of this artifice does not exceed ±3 db and occurs where the actual antenna height is approximately equal to the minimum effective antenna height.

Excerpted from Antenna Engineering Handbook by Jasik with permission of the publisher, McGraw-Hill Book Co., Inc.

Minimum Effective Antenna Height

Excerpted from Antenna Engineering Handbook by Jasik with permission of the publisher, McGraw-Hill Book Co., Inc.

Wherever the antenna heights are small compared with the wavelength, the received field intensity is ordinarily stronger with vertical polarization than with horizontal and is stronger over sea wate than over poor soil. In these cases the "surface-wave" cannot be neglected. This use of the term "surface wave" follows Norton's usage and is not equivalent to the Sommerfeld or Zenneck "surface waves."

The parameter *A* is the plane-earth attenuation factor for antennas at ground level. It depends upon the frequency, ground constants, and type of polarization. It is never greater than unity and decreases with increasing distance and frequency, as indicated by the following approximate equation:

$$A \approx \frac{-1}{1 + j\frac{2\pi d}{\lambda}(\sin\theta + z)^2}$$

where $z = \frac{\sqrt{\epsilon_0 - \cos^2\theta}}{\epsilon\theta}$ for vertical polarization

$z = \sqrt{\epsilon_0 - \cos^2\theta}$ for horizontal polarization

$\epsilon_0 = \epsilon - j60\sigma\lambda$

θ = angle between reflected ray and ground

= 0 for antennas at ground level

ϵ = dielectric constant of ground relative to unity in free space

σ = conductivity of ground, mhos/meter

λ = wavelength, meters

In terms of these same parameters the reflection coefficient of the ground is given by

$$R = \frac{\sin\theta - z}{\sin\theta + z}$$

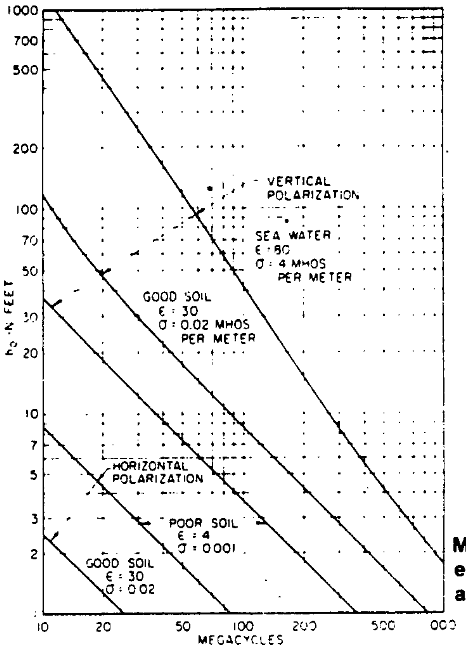
When $\theta \ll |z|$ the reflection coefficient approaches −1; when $\theta \gg |z|$ (which can happen only with vertical polzarization) the reflection coefficient approaches +1. The angle for which the reflection coefficient is a minimum is called the pseudo-Brewster angle, and it occurs when $\sin\theta = |z|$. As illustrated in the nomograph for transmission loss over plane earth, the effect of plane earth on the propagation of radio waves is given by

$$\frac{E}{E_0} = 1 + Re^{j\Delta} + (1 - R)Ae^{j\Delta} + \cdots$$

Direct wave | Reflected waves | "Surface wave" | Induction field and secondary effects of the ground

For antennas approaching ground level, the first two terms cancel each other (h_1 and h_2 approach zero, and *R* approaches −1) and the magnitude of the third term becomes

$$|(1 - R)A| \approx \frac{2}{(2\pi d/\lambda)z^2} = \frac{4\pi h_0^2}{\lambda d}$$



Minimum effective antenna height

where h_0 = minimum effective antenna height shown

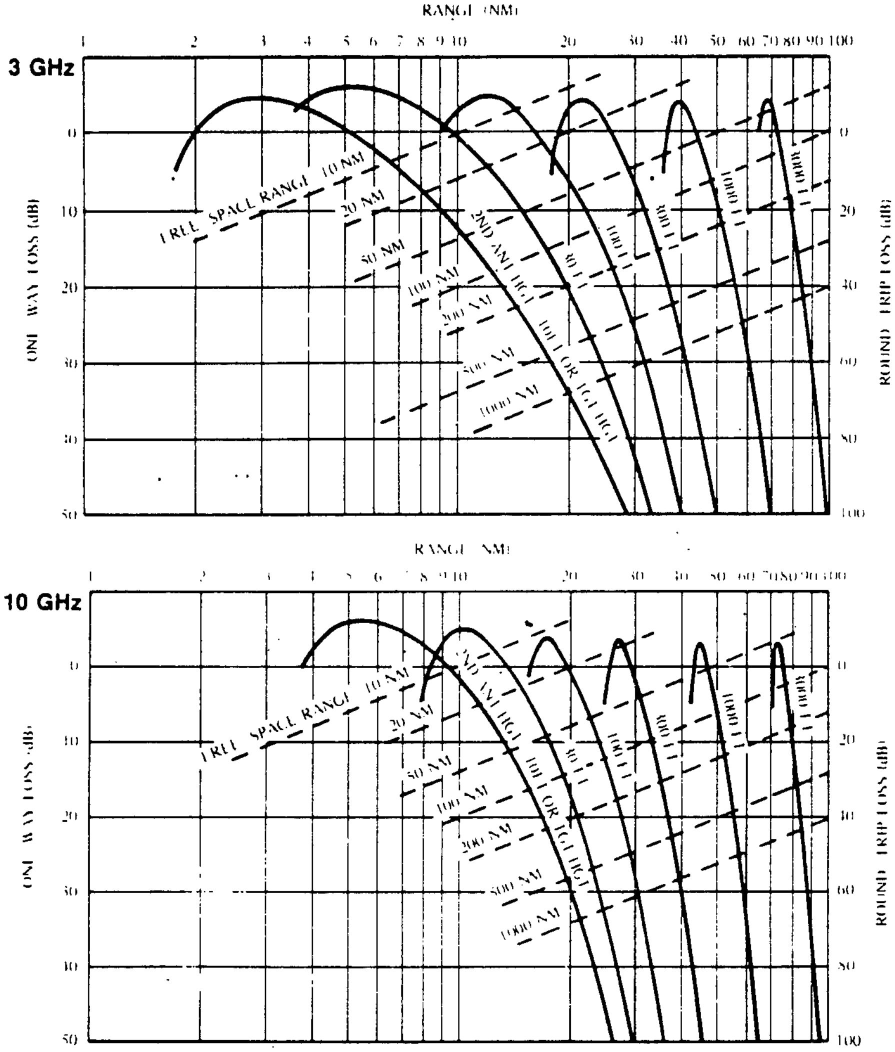
$$= \left|\frac{\lambda}{2\pi z}\right|$$

The surface-wave term arises because the earth is not a perfect reflector. Some energy is transmitted into the ground and sets up ground currents, which are distorted relative to what would have been the case in an ideal, perfectly reflecting surface. The surface wave is defined as the vertical electric field for vertical polarization, or the horizontal electric field for horizontal polarization, that is associated with the extra components of the ground currents caused by lack of perfect reflection. Another component of the electric field associated with the ground currents is in the direction of propagation. It accounts for the success of the wave antenna at lower frequencies, but it is always smaller in magnitude than the surface wave as defined above.

In addition to the effect of the earth on the propagation of radio waves, the presence of the ground may also affect the impedance of low antennas and thereby may have an effect on the generation and reception of radio waves. As the antenna height varies, the impedance oscillates around the free-space value, but the variations in impedance are usually unimportant as long as the center of the antenna is more than a quarter wavelength above the ground.

Propagation Loss and Detection Range for Low Altitude Targets over Water, Sea—State 1

1st Antenna Height: 100 ft Higher Order Lobes Not Shown



Propagation Loss Relative to Free-Space—Find the curve for altitude of the second antenna. Loss is given by the vertical scale as a function of range.

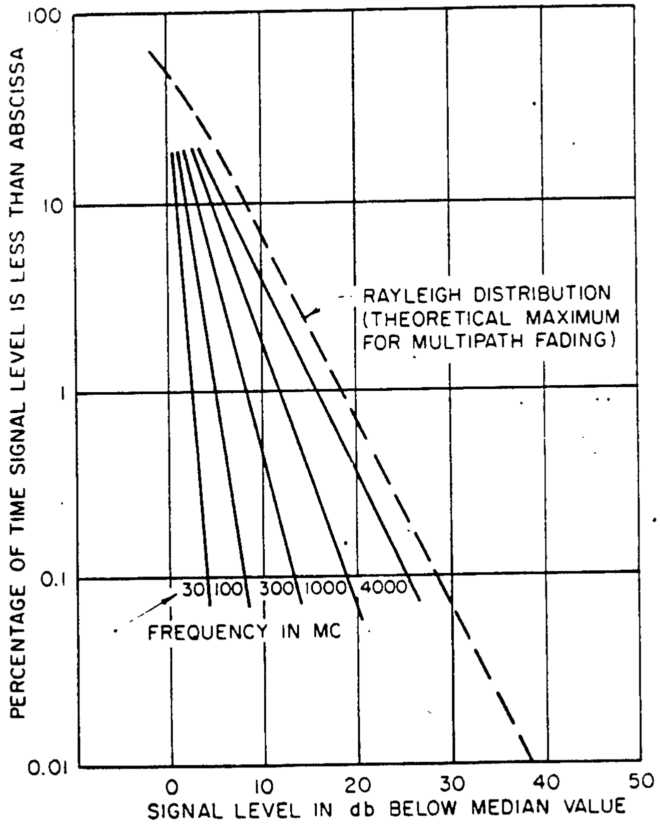
Detection Range of a Radar—Select the dashed line corresponding to the free-space detection range of the radar. Its actual range will be given by the abscissa of the intersection of the dashed line with the appropriate target height curve. Radar and target heights may be interchanged.

For ESM or Communications—Select the dashed line corresponding to the free-space operating range. The actual range will be given by the abscissa of the intersection of the dashed line with the appropriate antenna height curve.

Courtesy of Dynell Electronics Corporation, Melville, N Y

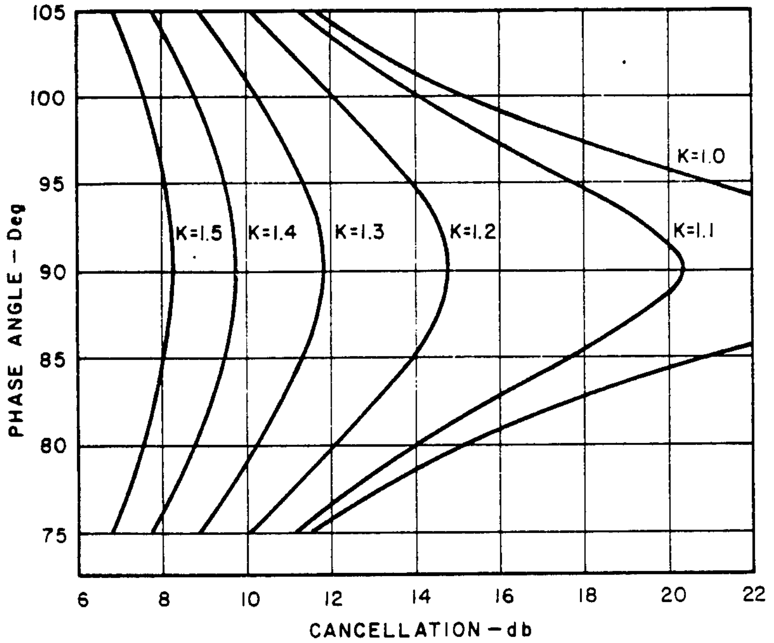
Fading Characteristics Resulting from Poor Atmospheric Conditions

At frequencies above 5,000 to 10,000 Mc, the presence of rain, snow, or fog introduces an absorption in the atmosphere which depends on the amount of moisture and on the frequency. During a rain of cloudburst proportions, the attenuation at 10,000 Mc may reach 5 db/mile and at 25,000 Mc it may be in excess of 25 db/mile. In addition to the effect of rainfall, some selective absorption may result from the oxygen and water vapor in the atmosphere. The first absorption peak due to water vapor occurs at about 24,000 Mc and the first absorption peak for oxygen occurs at about 60,000 Mc.



Typical fading characteristics in the worst month on 30- to 40-mile line-of-sight paths with 50- to 100-ft clearance.

Excerpted from Antenna Engineering Handbook by Jasik with permission of the publisher, McGraw-Hill Book Co., Inc.



$E_1 = E_1 \sin \omega t$

$E_2 = E_2 \sin (\omega t - \delta)$

$K = E_1/E_2$

$M = \tan \tau = \tan \left[\tfrac{1}{2} \arctan \frac{2K \cos \delta}{K^2 - 1} \right]$

E_b = minor axis of ellipse

E_a = major axis of ellipse

$\left(E_b/E_a\right)^2 = \frac{(1 - 2KM \cos \delta + M^2K^2)}{(M^2 + 2KM \cos \delta + K^2)}$

cancellation $= 20 \log_{10} \left[\frac{1 + (E_b/E_a)^2}{1 - (E_b/E_a)^2} \right]$

Two-way cancellation vs. phase angle for rain

Excerpted from Microwave Antenna Design supplement, May 1965 with permission of the publisher Hayden Microwaves Corporation

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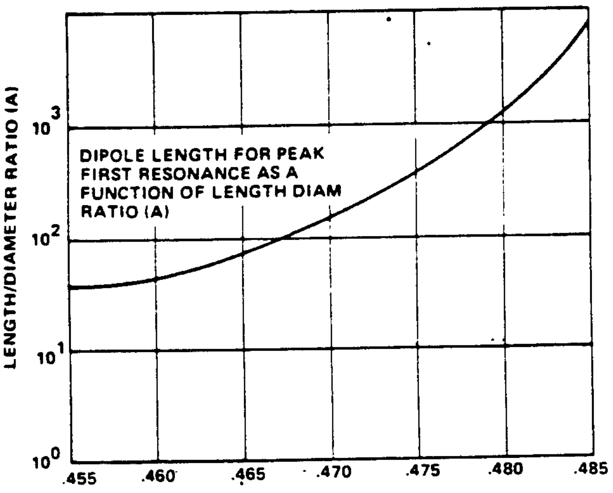
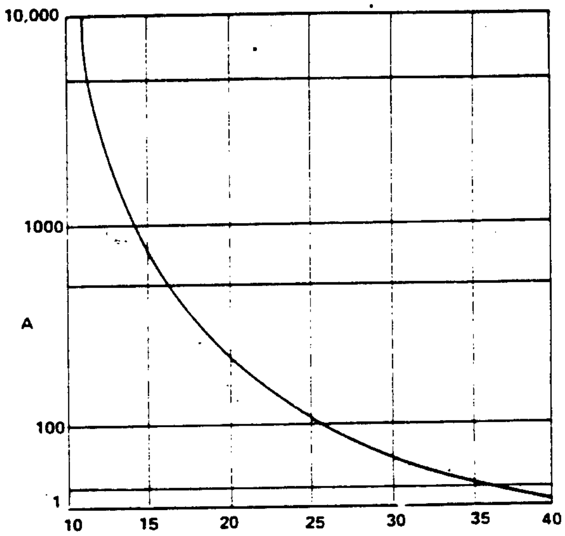
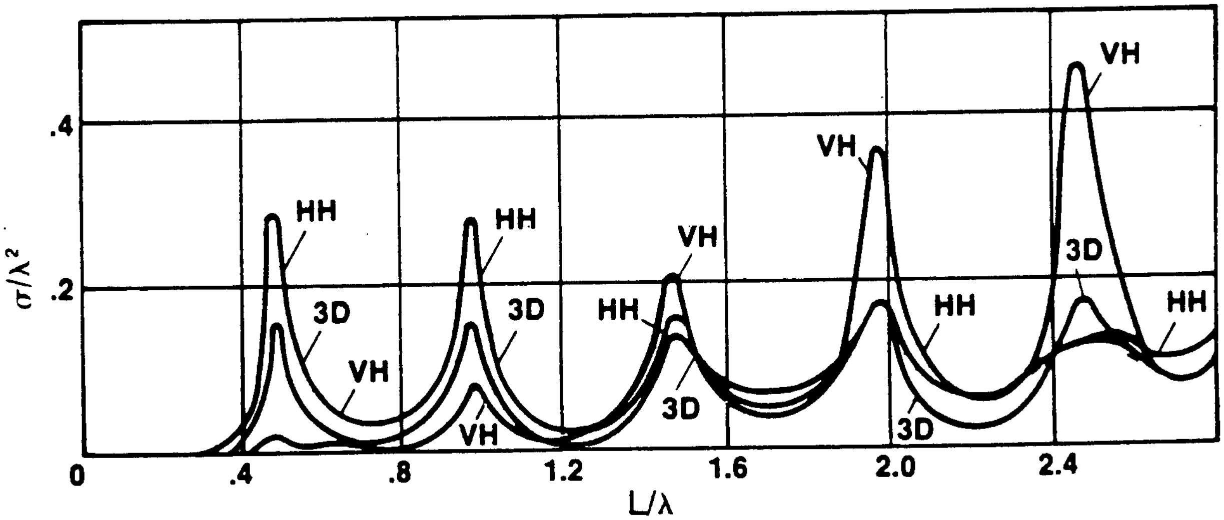
Chaff: Electronic Analysis



L/d vs. A at first resonance



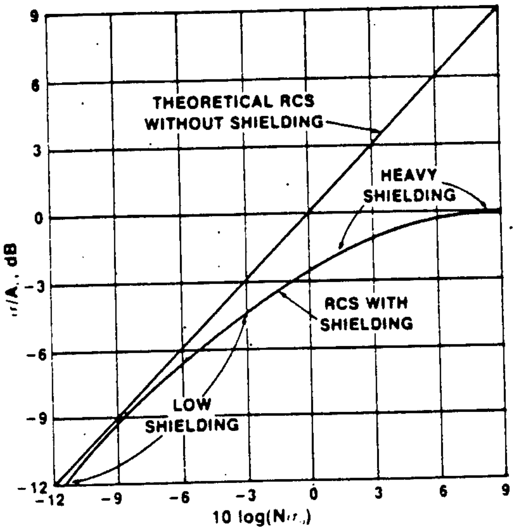
Dipole bandwidth at first resonance vs. A



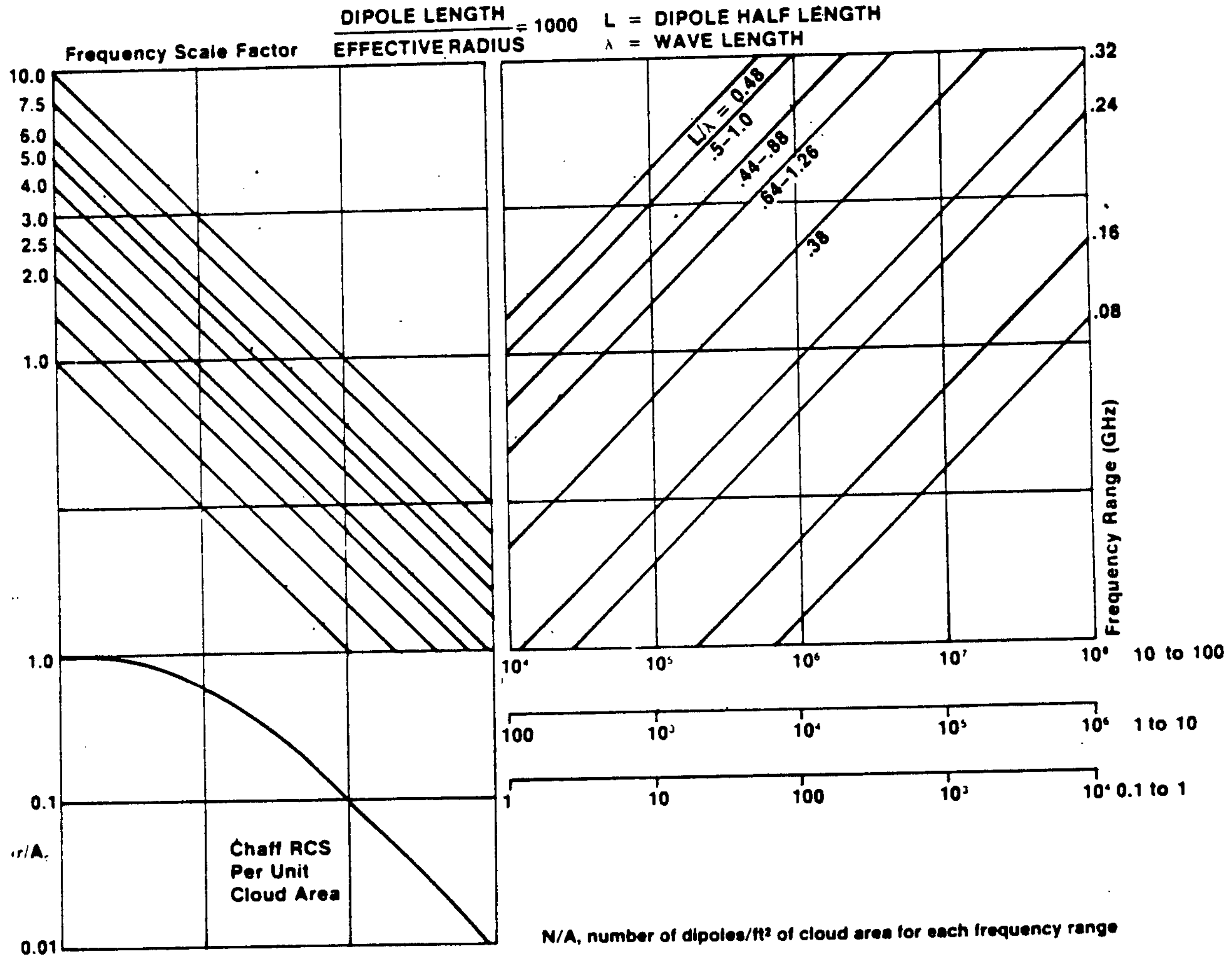
Polarization effects on σ/λ^2 in square wavelengths

CHAFF

In predicting the theoretical response of a cloud of dipoles, the fact that a dipole is located in a cloud of thousands of other dipoles results in a degradation effect known as shielding. This is a phenomenon which results when the dipole density of a cloud is such that it prevents every dipole from receiving the full amount of energy from the radar. This is one of the single most important effects present during the self-protection time period, and is predominant until the dipoles are separated by at least 10λ in the saturation time period.



Shielding effects



Chaff shielding nomogram

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